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COST Action CA17133

Implementing nature-based solutions for creating a resourceful circular city

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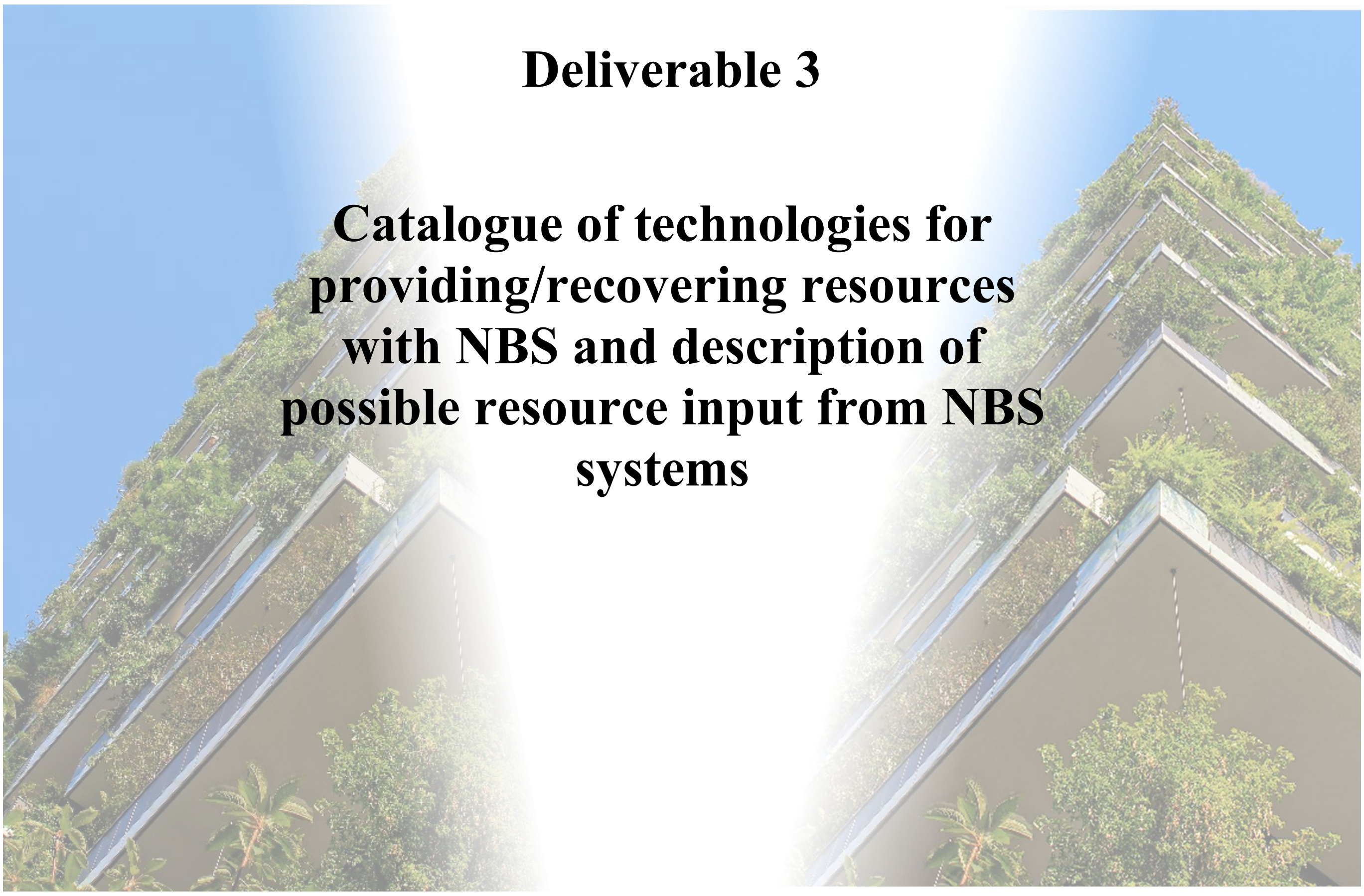

Deliverable 3

Catalogue of technologies for providing/recovering resources with NBS and description of possible resource input from NBS systems

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Disclaimer

For this deliverable, the COST Action Circular City launched a Special Issue on "Water and Circular Cities" in the MDPI journal *Water* (https://www.mdpi.com/journal/water/special_issues/water_circular_cities).

In total six papers were prepared for this Special Issue to describe the content of the deliverable, i.e. an introductory paper describing the conceptual approach, four papers of the Working Groups (WGs) 1-4 applying the conceptual approach described in the introductory paper, as well as a summary paper discussing the WG approaches as well as the way towards a cross-sectoral approach.

The table gives an overview of the status of the papers in the Special Issue "Water and Circular Cities" that are relevant for the content of the deliverable. In total 82 persons from 28 COST countries contributed to the six papers.

#	First author	Title	# authors	Status
1	Guenter Langergraber	A framework for addressing circularity challenges in cities with nature-based solutions (Framework paper)	9	Published
2	David Pearlmutter	Closing water cycles in the built environment through nature-based solutions: The contribution of vertical greening systems and green roofs (WG1 paper)	27	Published
3	Hassan Volkan Oral	Management of urban waters with Nature-Based Solutions in circular cities (WG2 paper)	23	Under review
4	Eric D. van Hullebusch	Selected nature-based solutions as building blocks for resource recovery systems in cities (WG3 paper)	22	Under review
5	Alba Canet-Martí	Nature-based Solutions for Urban Agriculture in Circular Cities: Challenges, Gaps and Opportunities (WG4 paper)	10	Published
6	Guenter Langergraber	Towards a cross-sectoral view on nature-based solutions for enabling circular cities (Summary paper)	19	Published

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1. The framework

A framework for addressing Urban Circularity Challenges (UCCs) with Nature-based Solutions (NBS) was developed in the COST Action. The framework has been formulated in Atanasova et al. (2021) aimed at mainstreaming the use of NBS for the enhancement of resource management in urban settlements. In Langergraber et al. (2021a) we present the framework that includes:

- The catalogue of technologies for providing/recovering resources with NBS that comprises a set of 39 NBS units (NBS_u), 12 NBS interventions (NBS_i), and 10 supporting units (S_u), as well as
- the analysis of input and output (I/O) resource streams required for NBS units and interventions (NBS_u/i).

The framework has been discussed from different perspectives that correspond to different urban sectors (i.e. the Action's WGs1-4) and activities relevant for the potential of circular management of resources.

Finally, the results from the WG-papers have been summarised and discussed in Langergraber et al. (2021b) with the aim to demonstrate that a holistic, cross-sectoral approach of implementing NBSs is necessary to account for the full potential of NBSs by presenting urban sector perspectives and identifying the interconnection of different sectoral views in various fields of application.

For this deliverable we summarise the catalogue of technologies for providing/recovering resources with NBS (Chapter 2) and the analysis of input and output (I/O) resource streams (Chapter 3). The aim of Chapter 2 is to provide the complete catalogue in one chapter so that it can be used as a stand-alone summary for this. In the Appendix, the six papers describing the main content of the deliverable in detail are added.

References:

Atanasova, N.; Castellar, J.A.C.; Pineda-Martos, R.; Nika, C.E.; Katsou, E.; Istenič, D.; Pucher, B.; Andreucci, M.B.; Langergraber, G. (2021): Nature-Based Solutions and Circularity in Cities. *Circ. Econ. Sustain*. 1, 319-332; doi:10.1007/s43615-021-00024-1.

Langergraber, G., Castellar, J.A.C., Pucher, B., Baganz, G.F.M., Milosevic, D., Andreucci, M.B., Kearney, K., Pineda-Martos, R., Atanasova, N. (2021a): A Framework for Addressing Circularity Challenges in Cities with Nature-based Solutions. *Water* 13, 2355; https://doi.org/10.3390/w13172355.

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2. Catalogue of technologies for providing/recovering resources with NBS

2.1. List of NBS units (NBS_u), NBS interventions (NBS_i) and Supporting units (S_u)

developed by the COST Action CA17133 Circular City (https://circular-city.eu/) (see Langergraber et al., 2021a)

Table 1: Descriptions and Synonyms/Subgroups of NBS units (NBS_u), NBS interventions (NBS_i) and Supporting units (S_u). Adapted from Langergraber et al. (2021a).

#	Units / Interventions	Synonyms/Subgroups	Descriptions
1	**Infiltration basin**	Green water storage and infiltration system; Storm basin; Non-permanent infiltration basin; Green water storage and infiltration system; Storm basin; Micro-catchment; The sponge zone (Castellar et al., 2021)	An **Infiltration basin** is a surface storage basin designed for short term temporal water storage by using an existing natural depression in the ground or by creating a new one. After a heavy rain, the water fills up the depression. The water then soaks into the ground or drains to the sewage system. If there is no heavy rainfall, the area is dry and could be used as a green area. Adapted from Castellar et al. (2021).
2	**Infiltration trench**	Percolation trench	**Infiltration trenches** are laminated systems with fabric-lined excavations atop a fabric-lined reservoir to increase infiltration. Adapted from UACDC (2010).
3	**Filter strips**	Vegetative filter strips	A **Filter strip** is a sloped medium that attenuates stormwater runoff by converting it into sheet flow and is typically located parallel to an impervious surface such as a parking lot, driveway, or roadway. Furthermore, the adoption of vegetated filter strips is increasing as they have been demonstrated to be effective for trapping runoff and sediment and promoting soil infiltration. Adapted from UACDC (2010) and Pan et al. (2018).
4	**Filter drain**	Filter trench; Surface sand filter	**Filter drains** are shallow trenches filled with stone/gravel that create temporary subsurface storage for attenuation, conveyance and filtration of surface water runoff. The stone may be contained in a simple trench lined with a geotextile, geomembrane or other impermeable liner, or with a more structural facility such as a concrete trough. Adapted from Woods-Ballard et al. (2015).
5	**(Wet) Retention pond**	(Wet) Retention basin; Wet pond; Wet pool Water Retention ponds; Green retention pond; Extended Retention Basin; Holding pond; Pond; (wet) retention basin (Castellar et al., 2021)	**(Wet) Retention ponds** consist of a permanent lagoon area with landscaped banks and surroundings to provide additional storage capacity during rainfall events. It has the capacity to continuously retain storm water, remove urban pollutants, and improve the quality of both surface runoff and release this at a controlled rate. During dry periods it also holds water. Adapted from Castellar et al. (2021).

6	**(Dry) Detention pond**	(Dry) Detention basin; Dry ponds	**Detention ponds**, or dry ponds, are stormwater basins designed to intercept stormwater runoff for temporary impoundment and metered discharge to a conveyance system or a receiving waterbody. In this regard, it can contribute to the prevention of urban flash flooding. Adapted from UACDC (2010).
7	**Bioretention cell**	Bioretention facility; Rain garden; Pluvial beds; BioFilter; Infiltration/stormwater planters; Infiltration garden; Rainfall garden; Water control garden, Floodable garden, Bio retention filter, Bio retention area, Bioremediation wet retention (Castellar et al., 2021)	A B**ioretention cell** is a shallow depressed vegetated area that primarily serves as a small-scale water control (storage and infiltration) area, especially in cities. It is designed to collect, store, filter, and treat water runoff. Storm water runoff is drained, stored for a certain period, and then it infiltrates either into the ground soil or flows into the sewage system. To optimise its functions, it must include a porous soil mixture, native vegetation and some hyper accumulator plants, capable of phytoremediation. Adapted from Castellar et al. (2021).
8	**Bioswale**	Swale; Green drainage corridor; Vegetative filter; Vegetated Bioswale (Castellar et al., 2021)	A **Bioswale** is a vegetated, linear and low sloped shallow pit or channel, often established in urban areas. It is designed to store and convey surface water runoff and also to remove pollutants and sediments. Furthermore, vegetation can intercept rainfall, increase subsurface water storage capacity, and improve infiltration. This NBS is often used to drain roads, paths or car parks while enhancing access corridors or other open space. Adapted from Castellar et al. (2021) and Xiao et al. (2017).
9	**Dry swale**	Grassed swale	A D**ry swale**, or grassed swale, is an open vegetated conveyance channel that filters, attenuates, and detains stormwater runoff as it moves downstream. Vegetation can include turf, meadow grasses, shrubs, and small trees (in limited quantities). Furthermore, the water flow through the swale can be slowed by a series of check dams. Adapted from UACDC (2010) and VA-DCR (2011).
10	**Tree pits**	Planters; Tree box; Tree pit filter	**Trees pits** and planters can be designed to collect and attenuate runoff by providing additional storage within the underlying structure. The soils around trees can also be used to directly filter out pollutant from runoff. (SUDS Manual). A tree box filter or in ground well consists of a container filled with amended soil and planted with a tree, underlain by crushed gravel media. Tree pits are attractive for stormwater control in dense urban areas because of their small size, low cost, and associated co-benefits that they bring by greening the streets. Adapted from UACDC (2010), Woods-Ballard et al. (2015) and Grey et al. (2018).
11	**Vegetated grid pavement**	Permeable/pervious/infiltration pavements; Green/greened/vegetated/grass pavements; green parking pavements; Engineered Vegetated Green Pavement; grass block paver/interlocking grass paver; Permeable pavements and parking lots; Pervious surfacing; Permeable	A **Vegetated grid pavement** includes planted pavement structures normally filled with soil, grass seeds, gravel or rocks. It can be considered as a type of pervious/permeable pavement. The runoff soaks through the pavement structure and can be stored or infiltrated into the ground. Accordingly, using permeable pavement is appropriate for decreasing the urban flooding problem and urban heat island effect. The structures are modular and adaptable to different surface types such as parking areas, roadways, cycle-pedestrian paths, sidewalks or street furniture zones. Usually, the costs and maintenance are low compared to traditional pavements. Adapted from Castellar et al. (2021) and Sun et al. (2018).

		green pavements (Castellar et al., 2021)	
12	**Riparian buffer**	Riparian buffer strip; Vegetative filter strips; Buffer strips	A R**iparian buffer** reduces surface runoff and detains sediments and sediment-bound pollutants from (mainly) agricultural areas. Located between agricultural catchments and streams/rivers, they act like filters for pollutants and sediment transportation into the river, slowing down the flow. They comprise hydric soil with facultative vegetation along the banks of a river or stream offering niche ecotone services. Riparian buffers provide a series of ecosystem services and functions such as reservoirs of biodiversity, flood mitigation, wetland products, bank protection, recreation, and water purification. Adapted from UACDC (2010) and Olokeogun and Kumar (2020).
13	**Ground-based green facade**	*Green facade*; Green facade with climbing plants; Climber green wall; Ground-based green-wall; Green climber wall; Green wall with ground-based greening; Climber plant wall; Ground-Based Green Facade with Climbing Plants; Soil-based green façade (Castellar et al., 2021)	A **Ground-based green facade** is a wall completely or partially covered with greenery. The climber plants are planted in the ground (soil, technical or recycling substrates) or in containers (filled with soil) and grow directly on the wall, or climb using climbing-aids (e.g., on a frame) that is connected to the wall. These NBS can also be implemented along highly frequented roads to reduce noise emissions. Adapted from Castellar et al. (2021).
14	**Wall-based green facade**	*Green wall;* Hydroponic green facade; Facade-bound greening; Facade bound green wall; living wall; Continuous green wall; Plant wall system; Green façade with vertical panels; Greening vertical panel; Vertical greening panel (Castellar et al., 2021)	A W**all-based green facade** (or green wall) comprises panels and technical structures (3D-frames filled with technical substrate) that are seeded or planted. These panels and structures are fixed onto facades or walls or can be designed as stand-alone system and allow the placement of plants and substrate on the entire surface. Some systems allow the removal of panels during winter time. Compared to soil/ground-based green facades a wider plant range can be applied for wall-based green facades. Adapted from Castellar et al. (2021).
15	**Pot-based green facade**	*Living wall; Planter green wall;* Planter green facade; Planter boxes; Planter pots; Planter-based green wall; Planted/planting container(s); Pot planted plants; Potted plants; Potted Mobile Garden; Raised bed; container plants (Castellar et al., 2021)	A **Pot-based green facade** involves the use of planted containers such as pots or planters, filled with artificial (technical) soilless substrate or soil or a mixture. They can be placed on the ground or directly on the building or balconies. They can be used with almost any kind of plants, e.g. climbing plants, trees and/or shrubs. Adapted from Castellar et al. (2021).
16	**Vegetated pergola**	Green pergola; Greened Pergola; Green matrasses Green shady	A V**egetated pergola** uses pillars, beams, stretched textile structure and lattices in different materials and compositions to create a growing assistance for vegetation and provide shaded areas. On this structure an inert

		structures; green shade (Castellar et al., 2021)	substrate can be installed, to be covered with seeds. Vegetated pergolas can be fixed to the facades of the buildings, on the street or by posts fixed to the sidewalk. Adapted from Castellar et al. (2021).
17	**Extensive green roof**	Green roof; Vegetated roof; Living roof (Castellar et al., 2021)	An **Extensive green roof** implies basic, light-weight, planted systems that are implemented on the rooftop of a building. The most common plants used are sedum, herbs, mosses, and grasses. The installation and maintenance are less expensive than that of intensive systems. The substrate is relatively thinner (10-15 cm, or reduced form > 10cm) than for intensive systems (more than 20 cm). Adapted from Castellar et al. (2021).
18	**Intensive green roof**	Green roof; Roof garden; Roof park; Vegetated roof; Living roof; Public Intensive Green Roof; Social Intensive Green Roof (Castellar et al., 2021)	An **Intensive green roof** consists of vegetation (higher variety than extensive green roof) that are installed on rooftops, normally accessible for public or recreation or gardening, relaxation and socialisation purposes. This NBS is usually heavier and has a deeper substrate (more than 20 cm) as compared to extensive systems. In addition, it requires more installation and maintenance effort such as regular irrigation and fertilisation, but provides more biotopes and higher biodiversity. Adapted from Castellar et al. (2021).
19	**Semi-intensive green roof**	Green roof; Smart roof; Vegetated roof; Living roof Biodiversity roof; Eco systemic roof (Castellar et al., 2021)	A **Semi-intensive green roof** is a combination of areas as intensive and extensive green roof. It is implemented on rooftops and is characterised by small herbaceous plants, ground covers, grasses, perennials and small shrubs, as well as higher growing plants, requiring moderate maintenance. The recommended minimum substrate thickness is between 12 cm (grass or herbaceous plants) and 20 cm (smaller shrubs and coppices), but can be adjusted. This type of green roof has higher maintenance than extensive systems and has the potential to host a richer ecology. Adapted from Castellar et al. (2021) and Vacek et al. (2017).
20	**Mobile green and Vertical mobile garden**	Mobile vertical greening; Mobile Green Living Room; Mobile green wall; Mobile vertical garden; Portable Green Wall; Mobile planter (Castellar et al., 2021)	These NBS units are mobile and thus can be located anywhere in the city. A **Mobile green** is usually organised as greened or planted containers or pots, that are removable. All plant types can be used for this NBS. For trees, large-scale containers are required. A **Vertical mobile garden** is a vertical, mobile, planted, self-supporting module. It is fixed to a hook lift container platform. On this structure, different layers are placed along a substrate (also hydroponic can be used) in which the plants can grow. Adapted from Castellar et al. (2021).
21	**Treatment wetland**	Constructed Wetland; Reed bed; Planted horizontal/vertical filters; Helophyte filter; Root-zone Wastewater Treatment; Natural wastewater treatment; Artificial Wetland; Planted sand/soil filters (Castellar et al., 2021)	**Treatment wetlands (TWs)** include a range of engineered systems designed and constructed to replicate natural processes occurring in natural wetlands involving vegetation, soils, and the associated microbial assemblages to assist in treating wastewater streams (e.g., domestic wastewater, greywater, industrial wastewater) and stormwater. TWs can be divided in two main hydrological categories: **Free water surface wetlands**, a shallow sealed basin or sequence of basins (open water areas) containing floating plants, submerged plants or emergent plants (similar in appearance to natural marshes); Subsurface flow wetlands, which include **Horizontal flow (HF) wetlands** and **Vertical flow (VF) wetlands**. In this case, the water flows beneath the surface level, either horizontally or vertically, through the filter bed. Adapted from Castellar et al. (2021) and Dotro et al. (2017).
22	**Waste stabilisation pond**	Wastewater Pond	**Waste stabilisation ponds (WSPs)** are earthen ponds designed and constructed in series, where sequential microbial metabolisms (anaerobic + facultative + aerobic) are established. WSPs utilise both physical and biological processes to remove organic materials, pollutants, and pathogens in raw wastewater The size of the

			infrastructure can be comparable to treatment wetland unit in some cases and it can be applied also for cities. Adapted from Von Sperling (2007) and Gruchlik et al. (2018).
23	**Composting**	Community composting; Compost heap; Composting facility (Castellar et al., 2021)	**Composting** includes all the structures and procedures required to compost food waste, vegetable materials, waste from cleaning grain, crop residues, etc. Adapted from Castellar et al. (2021).
24	**Bioremediation**		**Bioremediation** refers to bacteria- and fungi-based techniques to remediate contaminated soil and groundwater while simultaneously improving soil quality and providing ecosystem services. Bioremediation approaches can be applied *in situ* or *ex situ*, which depends on the nature of contaminant and site conditions. Adapted from Megharaj and Naidu (2017) and Zouboulis and Moussas (2011).
25	**Phytoremediation**		**Phytoremediation** refers to plant-based techniques to remediate contaminated soil and groundwater while simultaneously improving soil quality and providing ecosystem services. Phytoremediation is a cost effective, nonintrusive and aesthetically pleasing technology that removes contaminants by applying processes and mechanisms of degradation, sequestration, or transformation. Adapted from Olguín and Sánchez-Galván (2019) and Kurade et al. (2021).
26	**Anaerobic treatment** (for nutrient, VFA & methane recovery)		**Anaerobic treatment** refers to a treatment technology that stabilises organic wastes, or organic pollutants in wastewater, without the need for aeration. During anaerobic treatment, biodegradable organic compounds are mineralised, leaving inorganic compounds like NH4+, PO43-, HS- in the solution. Anaerobic treatment can be conducted in technically plain systems, and the process can be applied at any scale and at almost any place. During treatment, useful energy in the form of biogas (CH_4 and CO_2) or chemical building blocks like volatile fatty acids (VFA) are produced. Adapted from Van Lier et al. (2020).
27	**Aerobic (post) treatment** (for water recovery)		**Aerobic treatment** refers removal of pollutant under the presence of dissolved oxygen. In aerobic biological oxidation reactors, the conversion of organic matter is carried out by mixed bacterial cultures in general accordance with the following stoichiometry: COHNS+O_2+nutrients$\rightarrow$$CO_2$+$NH_3$+$C_5H_7NO_2$(new cells) + other end products. Examples of aerobic reactors are activated sludge and biofilm reactors. Aerobic autotrophic bacteria are responsible for nitrification (conversion of ammonium to nitrate) in these reactors. Adapted from Metcalf & Eddy (2002).
28	**River restoration**	River Re-naturing; River revitalization; Blue corridors; Soil-bioengineering for River Re-naturing; River restoration; River revitalization; Daylighting; Reopened stream; Channel widening and length extension; Reprofiling the channel cross-section; Channel reprofiling and re-	**River restoration** includes a set of techniques that aim on reducing pluvial flood risk and erosion. The river channel is widened or deepened, recovering part of its former channel, and enhancing the flood dissipation capacity. In case of covered/buried watercourses, the channel can be opened, by removing concrete layers. Both ways lead to an increment of storage capacity of the channel and natural development of the riverbed and riparian zone. Adapted from Castellar et al. (2021).

		opening; Fluvial restoration/rehabilitation; Deculverting and re-meandering (Castellar et al., 2021)	
29	**Floodplain**	*Reprofiling/extending floodplain;* Branches; Floodplain restoration; Floodplain widening; restore /increase the floodplain area; Room-for-the-river approach / Floodplain management (Castellar et al., 2021)	**Floodplains** aim to reduce flood risk by expanding the flood plain/water retention, thus providing additional flood space. Floodplain can be restored by excavating the lateral riverbed or by dividing the discharge into branches, by-passes, creating islands. During low water levels, these relatively flat and accessible bank areas can be used for multi-functional purposes. Floodplain restoration enables more efficient work of sewer and storm water pipe drainage systems by reducing their operational load and decreasing the need for expensive pipe solutions. Adapted from Castellar et al. (2021) and Fletcher et al. (2014).
30	**Diverting and deflecting elements**	Natural flow diversion structures; Redirection of water flow, Stimulation of river dynamic processes; Instream structures; (Soil and) Water Bioengineering for stream restoration; Water bioengineering flow changing techniques; Riverbed morphology engineering; Increased water course friction (Castellar et al., 2021)	**Diverting and deflecting elements** employ elements such as rocks, larger tree trunks, willow branches that are placed near the riverbank or in the middle of a river. These interventions alter flow variation and sediment shifting processes affecting the development of the channel's length and depth. In this sense, the main objective is to redirect, disturb, divert and deflect the water flow and initiate water dynamics for riverside protection against erosion. Adapted from Castellar et al. (2021).
31	**Reconnection of oxbow lake**		An oxbow lake is an ancient meander that was cut off from the river, thus creating a small lake with a U form. **Reconnecting of oxbow lake** with the river consists in removing terrestrial lands between both water bodies, therefore favouring the overall functioning of the river by restoring lateral connectivity, diversifying flows and cleaning the river section of the present oxbow for a better water retention during floods. The reconnection of oxbow lakes is also important for improving the diversity of riverine species. Adapted from Seidel et al. (2017).
32	**Coastal erosion control**		**Coastal erosion control** summarizes a set of techniques that aim to reduce coastal erosion by reducing wave velocity and trapping sediments. These technologies include coastal wetlands, salt marshes, large woody debris, coral and oyster reef systems, semi-permeable and permeable dams, etc. and techniques for sand dune restoration. Adapted from Davis et al. (2015) and Schueler (2017).
33	**Soil improvement and conservation**	Soil enhancement; Soil amendment Soil improvement and conservation measures; Soil enhancement(s); Gentle remediation options; Soil management; Engineered, improved soil (Castellar et al., 2021)	**Soil improvement and conservation** comprise several approaches to maintain and enhance soil quality in terms of physical, chemical and biological features. It aims to improve nutrient management, increase carbon storage, enhance water infiltration and retention, encourage beneficial soil organisms and prevent soil compaction. Some examples of specific techniques are: application of biochar, mulching, use of leguminous species for enhancing nitrogen fixation, use of organic matter, retaining stubble and green manuring to

			increase organic content and reduce compaction and erosion, organic fertilizer that stimulate and increase the soil biological activity and diversity. Adapted from Castellar et al. (2021).
34	**Erosion control**	Soil-bioengineering (slope); Soil (and Water) bioengineering for slope stabilization and erosion control; Soil & slope revegetation; Strong slope vegetation; slope vegetation/revegetation; Slope stabilisation through revegetation; Soil and slope stabilisation; Vegetation engineering systems for slope erosion control (Castellar et al., 2021)	**Erosion control** includes a set of different soil bioengineering techniques to stabilise soil structure on steepened slopes, to minimise/prevent the erosion of soil from wind or water, landslides and sedimentation problems. Common techniques are: revegetation (plants with strong deep roots), hydro-seeding, erosion control mat, covering natural fibre mats, wooden structures, and surface roughening. Adapted from Castellar et al. (2021).
35	**Soil reinforcement to improve root cohesion and anchorage**		**Soil reinforcement to improve root cohesion and anchorage** is induced by using live plant material for engineering purposes: woody plants and parts of plants (branches or stems) are placed in a constructive manner and according to defined design principles, e.g., brush layering, branch packing, live staking, fascine constructions. Furthermore, it is possible to use the construction waste for the reinforcement of soft soil foundation in coastal cities. This approach can decrease the cost of garbage removal and transportation, reduce the cost of foundation reinforcement, and also reduce the land occupation by waste. Adapted from Stokes et al. (2008) and Zhao et al. (2021).
36	**Riverbank engineering**	Riverbank engineering; Vegetation engineering systems for riverbank erosion control; Bioengineering (soil, water, fluvial, riverbanks); Riverbank stabilization/slope stabilization; Vegetated bank protection; Systems for erosion control on riverbanks; Riverbank protection system (Castellar et al., 2021)	**Riverbank engineering** techniques used in fluvial bioengineering for riverbank protection and hillside stabilisation to reduce risk of erosion by generating a natural protection. Some techniques embraced are: Planted embankment mat; Plants are established on hills with strong inclination to provide strong and branched root networks; engineered designs using plant material and woody plant parts (e.g. fascine constructions, willow branch mattress); Living and dead wood can be combined (e.g. Vegetated crib walls, dead and live wood branch packing) for linear application and wide-spread effects; live stakes and other plant elements can be used jointly or individually, to stabilise the slope (live stakes, root stocks, fascine brushes etc.). Adapted from Castellar et al. (2021).
37	**Green corridors**	Green way (Castellar et al., 2021)	**Green corridors** aim to renature areas of derelict infrastructure such railway lines or along waterways and rivers, transforming them into linear parks. This NBS can be considered as a transitional area between biomes that connect neighbourhoods. Green corridors can play an important role in urban green infrastructure networks and can offer niche, shelter, food and protection for the urban wildlife to survive and move from one green space patch to another. Adapted from Castellar et al. (2021).

38	**Green belt**	Green bypass	A **Green belt** is a green area surrounding built up area. It is a planning device designed to contain urban growth that is established for dividing urban and rural areas, and has the function to supress urban sprawl and provide recreational areas for residents. Adapted from Kowarik (2007) and Tang et al. (2007).
39	**Street trees**	Allée; urban trees; Trees on streets; Tree infrastructure; Planting and renewing urban trees; boulevards; urban tree canopy; Tree infrastructure; Urban trees alignment; single line trees; Sustainable management of urban trees; single tree (Castellar et al., 2021)	**Street trees** are focused on planting, renewing or maintaining urban street trees. It is designed to be appropriate for its context (right tree in the right place) and to achieve multiple benefits. One single or several trees can be arranged along streets, bicycle paths and sidewalks. These trees are situated on a single side (e.g. single line trees) and if circumstances allow, they can be established on both sides of the route (e.g. boulevard). In the latter case, the treetops of opposite trees often form a (nearly) closed canopy. Street trees support healthy urban communities through the provision of environmental, social and economic benefits. They improve cities liveability through provision of shade, stormwater reduction, improved air quality, and habitat connectivity for urban fauna. Social benefits are represented by the sense of community and safety, and reduced rates of crime. Regarding economic benefits, street trees can reduce energy costs and also increase the business income and property values Adapted from Castellar et al. (2021).
40	**Large urban park**	Urban park; Public park; Park; Green Park; Residential Park; City park Large urban public park; Greened recreation areas/regional parks; Green resting areas; City park (Castellar et al., 2021; FAO, 2016)	**Large urban park** refers to large green areas (>0.5 ha) within a city with a variety of active and passive recreational facilities that meet the recreational and social needs of the residents and of visitors to the city. They are open to wide-range communities. Large urban parks can serve all the city or part of city, and it is open to wide-range communities. Adapted from Castellar et al. (2021).
41	**Pocket/garden park**	Small Park; Neighbourhood park; Landscape park; Empowerment Park; Pocket parks (Castellar et al., 2021; FAO, 2016)	**Pocket or garden parks** are publicly accessible and compact green areas or small gardens (<0.5 ha) around and between buildings vegetated by ornamental trees, grass and other types of plants. The area is projected for resting, relaxation, observing nature, social contact and physical health. Pocket or garden parks provide opportunities for people to create small but important public spaces right in their own neighbourhoods. Adapted from Castellar et al. (2021).
42	**Urban meadows**	Urban wildflower meadows	**Urban meadows** are species-rich grasslands created over a longer period of time, which are beneficial to native wildlife in the urban environment. The type of meadow created and method used to create and manage them will vary with conditions, habitat and budget. The benefits of implementing urban meadows (instead of mown grass in urban public greenspaces) are evident for urban biodiversity, human wellbeing and for local economy as a cost-effective solution. Adapted from Hoyle et al. (2017).
43	**Green transition zones**		**Green transition zones** between high vegetation (urban forests and parks mainly) and adjacent areas or infrastructure and embedded in urban environments, functioning as enriching spatial units (ecotones) in the landscape, requiring special(ised) management and providing different, including in quality or extent NBSs in comparison with bordering spaces or ecosystems. Vegetation transitions, or ecotones, represent border regions of transition between communities, ecosystems or biomes, that reflect both local and regional changes in abiotic conditions. Adapted from Oliveras et al. (2016) and Kark and van Rensburg (2006).

44	**Aquaculture**	Flow-through fish farm; Recirculating Aquaculture Systems (RAS)	**Aquaculture** is the farming of aquatic organisms, including fish, molluscs, crustaceans and aquatic plants. Farming implies some form of intervention in the rearing process to enhance production, such as regular stocking, feeding, protection from predators, etc. Farming also implies individual or corporate ownership of the stock being cultivated. Aquaculture includes Flow-through fish farm as well as Recirculating Aquaculture Systems (RAS). Aquaculture has potentials for providing the lower priced fish, enhance nutritional security and employment of poor urban communities. Urban aquaculture can decrease the distance between farm and plate, generate income, use less resources, and serve as a community building tool. Adapted from Roan et al. (2019).
45	**Hydroponic and soilless technologies**		**Hydroponics** is an agricultural method that provides soilless plant growth by applying the mixture of water and nutrient solution that is controllable and can be delivered to plants based on their needs. This system provides improved control of plant's nutrition, efficient use of space, and the possibility of saving fertilizers. Greenhouses with hydroponic systems are seen as sustainable systems for growing food in cities with improved control of plant growth. The huge potential offered by this cultivation approach ranges from productive and qualitative advantages to environmental benefits due to higher efficiency in using water and nutritional resources, NO_3-management and crop quality increase. Adapted from Christie (2014); Rufí-Salís et al. (2020) and Sambo et al. (2019).
46	**Organoponic / Bioponic**		**Organoponic / Bioponic** is an emerging soilless technology for nutrients recovery that links organic vegetable production to organic effluent remediation or organic waste recycling (adapted from Wongkiew et al., 2021). Bioponic production describes a contained and controlled growing system in which plants in growing media derive nutrients from natural animal, plant and mineral substances that are released by the biological activity of microorganisms (Allen et al., 2016).
47	**Aquaponic farming**	Aquaponics; Trans-aquaponics	**Aquaponic farming** comprises aquaponics (which couples tank-based animal aquaculture with hydroponics) as well as trans-aquaponics, which includes integrated aqua-agriculture systems exploiting the aquaponic principle without these restrictions. Adapted from Baganz et al. (2021).
48	**Photo Bio Reactor**		A **Photo Bio Reactor (PBR)** is defined as a closed (or mostly closed) vessel for phototrophic production in which the energy is supplied via electric lights. A PBR design should use light efficiently with uniform illumination, should reduce shading and provide a fast mass transfer of CO_2 and O_2, and should attain high biomass growth. Adapted from Andersen (2005) and Gupta et al. (2015).
49	**Productive garden**	Market garden; Community garden; Mobile vertical garden (with substrate or soil)	**Productive gardens** are areas of land dedicated to the cultivation of vegetables, fruits (fruit trees), (flowers) and small livestock (chicken) for the main purpose of food production (which output have a significant share on food production). These gardens can be differently owned, yet ownership has no effect in terms of the function of the NBS unit. Adapted from Castellar et al. (2021).
50	**Urban forest**	Group of trees; Wood; Urban woodland; Arboreal areas around urban areas; Arboreal urban parks;	An **Urban forest** mimics the appearance/form of a forest in an urban setting. It comprises all woodlands, groups of trees, and individual trees, forests, street trees, trees in parks and gardens, and trees in derelict corners. Usually, urban forests are managed and enables foraging for food. Benefits of urban forests range

		Arboretum; Urban tree cover (Castellar et al., 2021)	from psychological, aesthetic, recreational and health benefits to amelioration of urban climate, mitigation of air pollution to increased urban biodiversity. Adapted from Castellar et al. (2021).
51	**Urban farms and orchards**	Small-scale farms	**Urban farms and orchards** are agriculture ventures dedicated to food production in a city, often professionally run and considerably larger than gardens. Food production may include big livestock (cows), fruits (fruit trees), and main food crops (maize, wheat). Larger urban farms also participate in community programmes such as skills development and job training that can benefit underserved populations. Furthermore, as a form of green infrastructure, urban farms and community gardens can help reduce urban heat island effects, mitigate the impacts of urban stormwater and lower the energy embodied in food transportation. Adapted from Ackerman et al. (2018).
S1	**Rain Water Harvesting**		**Rainwater harvesting** (RWH) in cities consists of concentration, collection, storage and treatment of rainwater from rooftops, terraces, courtyards, and other impervious surfaces for on-site use, with the aim to reduce drinking water consumption from centrally supplied sources. Rainwater harvesting reduces runoff volume and peak flows. Rainwater can be collected in cisterns, bladder tanks, and precast ferrocement septic tanks. Adapted from UACDC (2010) and Campisano et al. (2019).
S2	**Detention vaults and tanks**	Wet vaults; Dry vaults; Attenuation storage tanks	**Detention vaults and tanks** are underground storage/treatment facilities constructed of reinforced concrete (vaults) or corrugated pipe (tanks). They may be used to handle general site runoff, or they may be dedicated to the runoff from impervious surfaces such as roofs and parking lots. Detention vaults may be designed to empty completely between storms (dry vaults), or they may be designed to maintain a permanent water pool (wet vaults). These facilities provide runoff volume control, peak discharge reduction, sediment control, and harvesting potential. Adapted from UACDC (2010).
S3	**Phosphate precipitation** (for P recovery)		**Phosphate precipitation** refers to the chemical precipitation of Phosphorus is brought about by the addition of the salts of multivalent metal ions that form precipitates of sparingly soluble phosphates. The multivalent metal ions used most commonly are calcium, aluminium and iron. For struvite precipitation magnesium is added, Struvite precipitation is controlled by a combination of physio-chemical factors including temperature, mixing energy, pH, the degree of Mg, NH4, and PO4 supersaturation, and the presence of competing ions. Magnesium generally needs to be added. Adapted from Metcalf & Eddy (2002) and Hallas et al. (2019).
S4	**Ammonia stripping** (for N recovery)		Gas stripping (like dissolved ammonia) involves the mass transfer of a gas from the liquid phase to the gas phase. The transfer is accomplished by contacting the liquid containing the gas (ammonia) that is to be stripped with a gas (usually air) that does not contain the gas initially. For **Ammonia stripping**, the ammonia stripped from the wastewater is converted to ammonium by passing the off-gas through an acid bath/scrubber. Adapted from Metcalf & Eddy (2002).
S5	**Disinfection** (for water recovery)		**Disinfection** describes a process that eliminates pathogenic microorganisms the use of chemical agents (like chlorine and its compounds), physical agents (like light, heat and sound), mechanical means and radiation. Adapted from Metcalf & Eddy (2002).

S6	**Biochar/Hydrochar production**	**Biochar** is a carbon-rich solid by-product produced through high-temperature pyrolysis or degasification of organic material under low or no oxygen environment, which prevents combustion. Biochar is being used in an increasing number of fields and has been widely employed in a variety of applications, such as an adsorbent, a source of nutrients, and soil amendment agent where the biochar amendment could further suppress plant diseases as well. Properties of biochar and its applications are highly influenced by the mode of preparation and type of feedstock used. High moisture containing feedstocks are converted into biochar (hydrochar) with the help of hydrothermal carbonization (HTC). Adapted from Gabhane et al. (2020).
S7	**Physical unit operations for solid/liquid separation**	**Physical units for solid/liquid separation** mostly used in wastewater treatment are screening, grit removal, sedimentation, high rate clarification, accelerated gravity separation, (bio-) flocculation and flotation. Adapted from Metcalf & Eddy (2002).
S8	**Membrane filtration**	During **Membrane filtration,** the role of a membrane is to serve as a selective barrier that will allow the passage of certain constituents and will retain other constituents found in the liquid. Adapted from Metcalf & Eddy (2002).
S9	**Adsorption**	**Adsorption** is the process is the process of accumulating substances that are in solution on a suitable interface. Activated carbon treatment of wastewater is usually thought of as a polishing step, for example for removing micro-pollutants like pharmaceuticals, personal care products and hormones. Adapted from Metcalf & Eddy (2002).
S10	**Advanced Oxidation Processes (AOP)**	**Advanced oxidation processes (AOP)**, like ozone treatment, are used to oxidize complex organic constituents found in wastewater, that are difficult to degrade biologically (for example micro-pollutants), into simpler end products. Adapted from Metcalf & Eddy (2002).

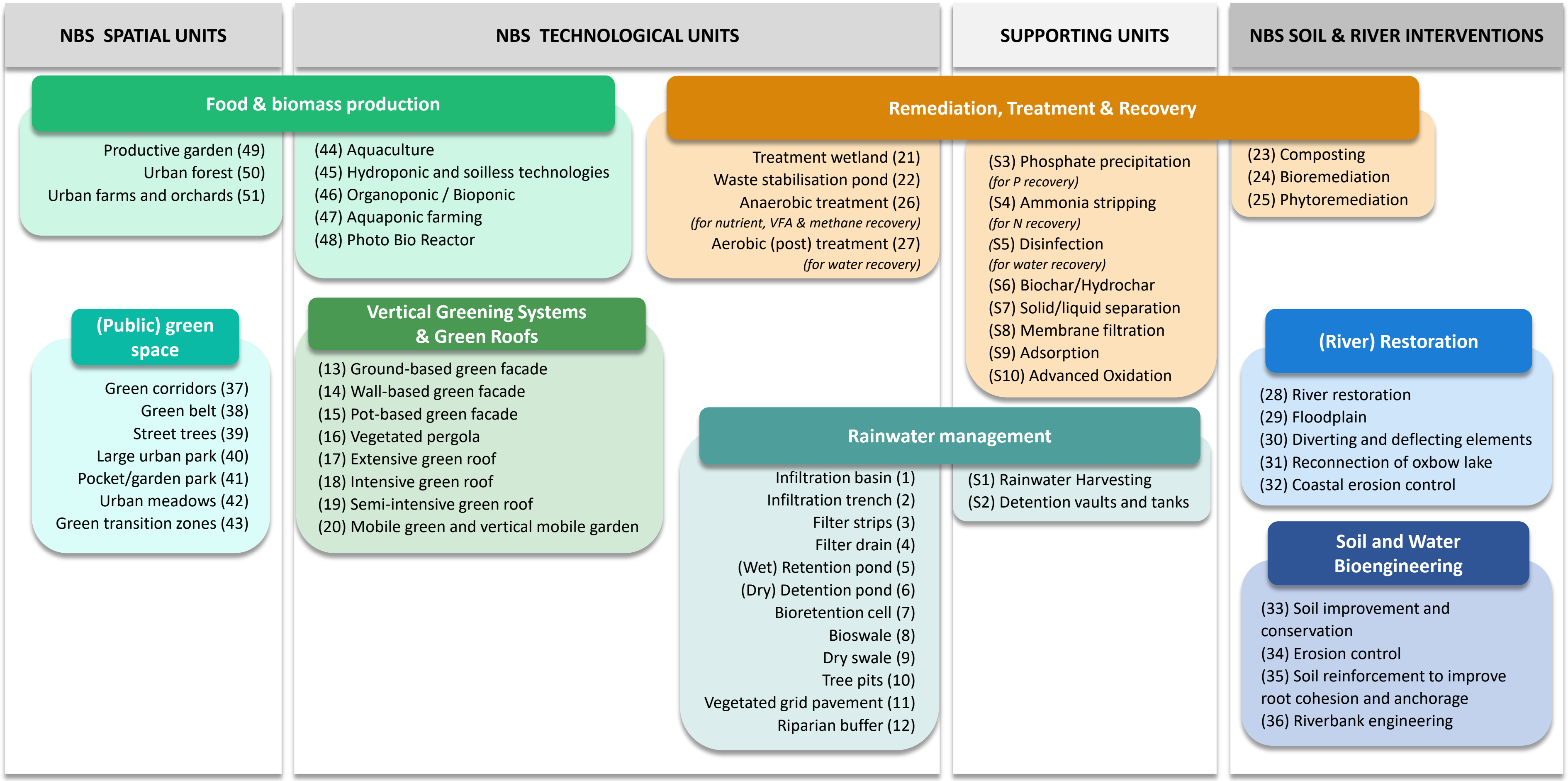

Figure 1: NBS units (NBS_u), NBS interventions (NBS_i) and Supporting units (S_u) clustered into categories (dark grey squares, adapted from Castellar et al. (2021) and sub-categories proposed by consulted experts within the COST Action Circular City (coloured squares) (from Langergraber et al., 2021a).

2.2. Urban Circularity Challenges (UCCs) addressed and relevance for different sectors

Table 2: Urban Circularity Challenges (UCCs) addressed by NBS units and interventions (NBS_u/i) and Supporting units (S_u) (Langergraber et al., 2021a), and Relevance of NBS units and interventions (NBS_u/i) and supporting units (S_u) for different sectors, i.e., working groups of the COST Action Circular City (Langergraber et al., 2021b). NBS_tu = technological units; NBS_su = spatial units; NBS_is = interventions; NBS_ir = river interventions; and S_u = Supporting unit.

			Urban Circularity Challenge (● = addressing the challenge; ● = contribution to challenge mitigation; ○ = potential contribution, depending on the design; and as an "empty cell" = not addressing the challenge)							**Urban Sectors** (● = relevant; ○ = might be relevant, depending on system design)				
Classification		**(#) NBS Units, NBS Interventions, and Supporting Units**	**Restoring and Maintaining the Water Cycle**	**Water and Waste Treatment, Recovery and Reuse**	**Nutrient Recovery and Reuse**	**Material Recovery and Reuse**	**Food and Biomass Production**	**Energy Efficiency and Recovery**	**Building System Recovery**	**Building Systems**	**Building Sites**	**Urban Water Management**	**Resource Recovery**	**Urban Farming**
Rainwater Management	*NBS_tu*	(1) **Infiltration basin**	●	●			○	○			●	●	●	○
		(2) **Infiltration trench**	●	○							●	●	●	
		(3) **Filter strips**	●	●							●	●		
		(4) **Filter drain**	●	●							●	●		
		(5) **(Wet) Retention pond**	●	●		○	○				●	●	●	○
		(6) **(Dry) Detention pond**	●	●							●	●		
		(7) **Bioretention cell**	●	●	●	○	○		●	●	●	●		○
		(8) **Bioswale**	●	●			○				●	●		○
		(9) **Dry swale**	●	○			○				●	●		○
		(10) **Tree pits**	●	●	●		○	●			●	●		○
		(11) **Vegetated grid pavement**	●	●			○	●			●	●		○
		(12) **Riparian buffer**	●	●	●		●	○			●	●		●
	S_u	(S1) **Rainwater harvesting**	●	○				●	○	●		●		
		(S2) **Detention vaults and tanks**	●	○					●	●		●		

Vertical Greening Systems & Green Roofs	*NBS_tu*	(13) **Ground-based green facade**	●	●			●	●	●	●		●		●
		(14) **Wall-based green facade**	●	●	○	○	●	●	●	●		●		●
		(15) **Pot-based green facade**	●	●	○		●	●		●		●		●
		(16) **Vegetated pergola**	○	●		○	●	●		●	●	○		●
		(17) **Extensive green roof**	●	○			●	●	●	●		●		●
		(18) **Intensive green roof**	●	●	○	○	●	●	●	●		●		●
		(19) **Semi-intensive green roof**	●	●	●	○	●	●	●	●		●		●
		(20) **Mobile green and vertical mobile garden**	○	●			●	○			●	○		●
Remediation, Treatment & Recovery	*NBS_tu*	(21) **Treatment wetland**	●	●	○	○	●	●	○	●	●	●	●	●
		(22) **Waste stabilization pond**	●	●								●		
		(26) **Anaerobic treatment**	●	●	●	○		●				●	●	
		(27) **Aerobic (post) treatment**	●	●								●	●	
	NBS_is	(23) **Composting**			●	●	●	●		●	●		●	●
		(24) **Bioremediation**	○	○		○			○		●	○	●	
		(25) **Phytoremediation**	○	○	○	○	●		○		●	○	●	●
	S_u	(S3) **Phosphate precipitation** (for P recovery)	●	●	●							●	●	
		(S4) **Ammonia stripping** (for N recovery)	●	●	●							●	●	
		(S5) **Disinfection** (for water recovery)	●	●					●	●		●	●	
		(S6) **Biochar/Hydrochar production**	●	●		●	●					●	●	●
		(S7) **Physical unit operations for solid/liquid separation**	●	●		●	●		●			●	●	●
		(S8) **Membrane filtration**	●	●		●			●			●	●	
		(S9) **Adsorption**	●	●	○	○						●	●	
		(S10) **Advanced Oxidation Processes**	●	●								●	●	
(River) Restoration	*NBS_ir*	(28) **River restoration**	●	●			●				●	●		●
		(29) **Floodplain**	●	●			●				●	●		●
		(30) **Diverting and deflecting elements**	○								●	○		

		(31) **Reconnection of oxbow lake**	●	●							●	●		
		(32) **Coastal erosion control**	●				○				●	●		○
Soil & Water Bioengineering	*NBS_is*	(33) **Soil improvement and conservation**	○	○	●	●	●		●		●	○	●	●
		(34) **Erosion control**	○	○	●		○		○		●	○		○
		(35) **Soil reinforcement to improve root cohesion and anchorage**	○						○		●	○		
		(36) **Riverbank engineering**	○	○			○				●	○		○
(Public) Green Space	*NBS_su*	(37) **Green corridors**	●	●			●				●	●		●
		(38) **Green belt**	●	●			●		○		●	●		●
		(39) **Street trees**	●	●		○	●		○		●	●	●	●
		(40) **Large urban park**	●	●		○	●	○	○		●	●	●	●
		(41) **Pocket/garden park**	●	●		○	●	○	○		●	●	●	●
		(42) **Urban meadows**	●	●		○	●		○		●	●		●
		(43) **Green transition zones**	●	●		○	●	○	○		●	●		●
Food & Biomass Production	*NBS_tu*	(44) **Aquaculture**		○			●	○	●					●
		(45) **Hydroponic and soilless technologies**	○	○			●	○	●	●		○		●
		(46) **Organoponic/Bioponic**	○	○	●		●	○	●	●		○		●
		(47) **Aquaponic farming**	○	●			●	○	●	●		○		●
		(48) **Photo Bio Reactor**	●	●	●	○	●	●				○	●	●
	NBS_su	(49) **Productive garden**	●	●	○		●	●	○	●	●	●		●
		(50) **Urban forest**	●	○			●	●	●		●	●		●
		(51) **Urban farms and orchards**	●	●	●		●	○	●		●	●		●

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3. Description of possible resource input from NBS systems

3.1. Input and output (I/O) streams

Understanding the role of NBS in optimizing the flow of different streams is a very important step to promote their implementation for circular cities. The possible input and output (I/O) streams have been defined in Langegraber et al. (2021a). Inputs (I) required for operation and maintenance of NBS_u/i and S_u and potential Outputs (O) produced by NBS_u/i and S_u are considered as streams (elements and resources flowing through NBS). As inputs, these streams are required for the operation and maintenance of NBS, and thus, they can come from or be produced by other NBS or from other parts of the urban system. As outputs, the streams present resources to be recovered and provided for holistically operating NBS in circular cities, and thus, they are essentially produced by NBS and can flow to other NBS or to other parts of the urban production chain. In the course of the elicitation workshops, five streams were identified (water, nutrients, biomass, living organisms, and energy), comprising over 20 categories (Figure 2).

Figure 2: Main types of streams and respective categories of inputs required for the operation and maintenance of NBS and/or outputs potentially produced by NBS in circular cities (Langegraber et al., 2021a).

3.2. System Analyses of Resource Streams

To support the transition toward circular resource flows, information on these streams is needed. System analysis was used to study the CE network topology (Figure 1). The network consists of nodes and links. Nodes are CE entities, circular city entities, or NBS units (NBS_u)—black boxes for which only input and output (I/O) are known. They are linked by resource streams. Since the nodes are seen as black boxes, system internal streams (which can also be circular) are not considered in the information model. Whether a stream is internal or external depends on the design of the model; ownership is usually a good delineation. For example, in a trans-aquaponics case, where a treatment wetland is used for aquaculture wastewater and sludge removal (Baganz et al., 2021), internal streams become external if the coupled production units have different owners.

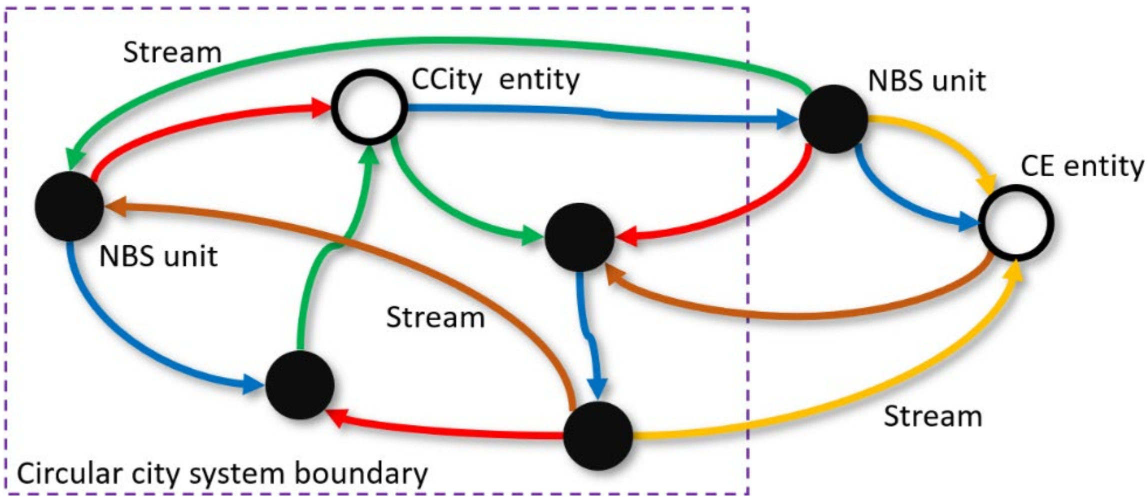

Figure 3: Schematic sketch of a CE network topology with CE and Circular City entities (referred to as "CCity entities") as black boxes (nodes) and unidirectional resource streams (links). Circular Economy entities (referred to as "CE entities") within the Circular City system boundary become Circular City entities. All full circles represent NBS units, regardless of the Circular City system boundary. The link colors symbolize the stream types of water, nutrients, biomass, living organisms, and energy but do not represent specific streams in this sketch (Langegraber et al., 2021b).

3.3. A Streams Information Model to Describe Inputs and Outputs

A recently published model (Baganz et al., 2020) was further developed by reducing its scope and concomitantly qualifying the model elements, adjusted to the requirements of the COST Action Circular City with a focus on streams as a 'streams information model'. It waived the site model element, integrated the 'extended resource specification' as stream properties, and added the circular city system boundary, allowing the circularity between NBS_u/i and other CE entities. A unified terminology was developed to describe the requirements for resource streams from and to NBS, which were applied to all streams, notwithstanding differences of the individual streams. In this model, we abbreviate NBS_u/i as NBS.

The first part of the model (Figure 4) comprises CE entities as the nodes and refer to an entity type which is qualified by attributes, e.g., 'is natural feature'. In the present model, NBSs are considered special cases of CE entities, marked as 'is NBS unit', and comprise all NBS_u/i and S_u (Langegraber et al., 2021a). The concrete instance of an NBS_u/i or S_u has a name as a unique identifier and is located at a concrete place, and, if this location is within the system boundaries of the circular city, the property 'within circular city boundary' is set, making the NBS an entity of the circular city (CCity entity). In an implementation of the model, the assignment can be done automatically by a geographical information system (GIS).

The links between the CE entities are resource streams, which are hierarchically ordered by a complete set of types (water, nutrients, biomass, living organisms, and energy), divided into categories and subcategories, depicted by a comprehensive set of examples. Furthermore, they have a measuring unit which qualitatively describes a stream and can be used to quantify the flow volume. Streams have different endpoints: CE/CCity entities, NBS_u/i, or natural features, such as the atmosphere as a source of precipitation. Each NBS_u/i has at least one input (I) and one output (O) stream such that their cardinality is 1 to *n* in each case.

In conjunction with the endpoints, streams represent resources that are uniquely identified by (1) the entity (e.g., NBS_u/i or S_u) which is using a stream, (2) the stream subcategory, and (3) the interface direction of the NBS_u/i where 'input' is equal to demand and 'output' is equal to the supply of the respective stream. Whether a stream is output (O) or input (I) depends on the respective endpoint.

The resources have optional properties, such as flow characteristics, which describe whether a resource is permanently available, discontinuous, on demand, or adaptable. However, the annual quantity, statements on quality, whether spatial proximity is required, the possible use of utility grids, or the purpose of the resource can also be specified.

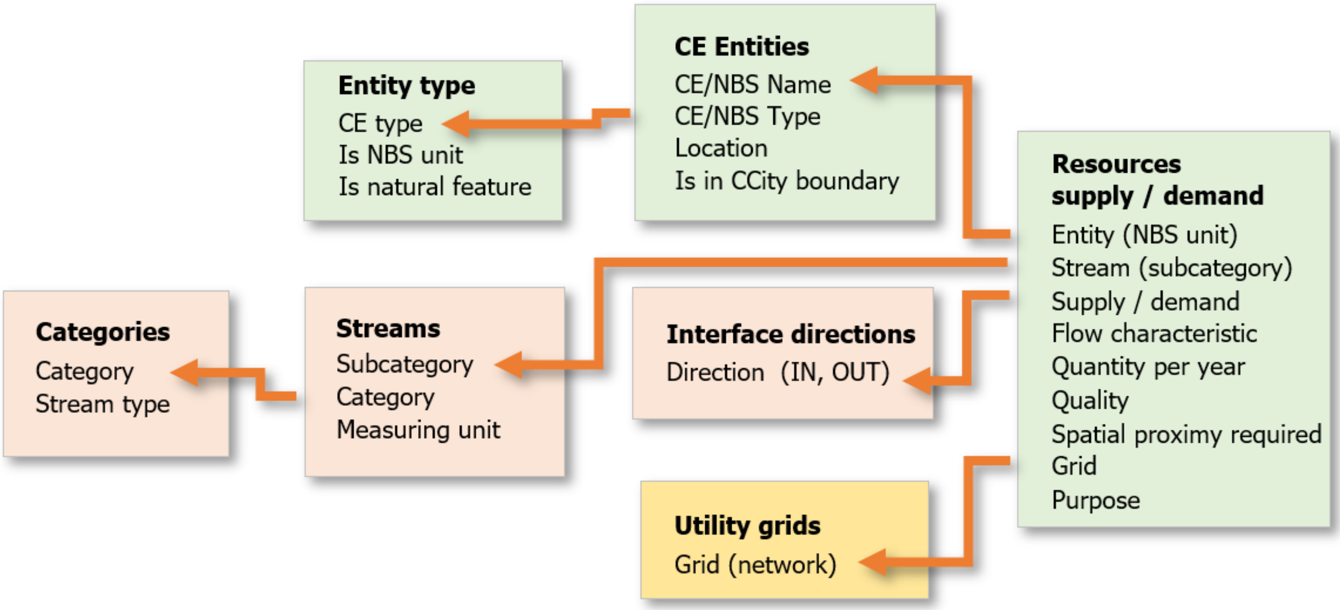

Figure 4: An information model on NBS_u/i and interconnecting streams (Figure 2). Green: entities and their resources; red: streams; yellow: grids (optional) (Langegraber et al., 2021b).

A stream connects two endpoints directionally and runs as output (O) from one endpoint to the input (I) of the other endpoint. This simplest form of resource use is linear and can occur in isolation in many places in the city. However, to implement a resource network which features circularity, it is necessary to connect these linear elements so that they form loops. Various loops can be formed within the system boundaries of the circular city; however, to create this network of loops, data on the quality and quantity of streams are required to fit the supply/demand of the respective endpoints. Nevertheless, there is still a considerable need for interdisciplinary research in order to be able to determine these stream characteristics.

The streams information model can be understood as a template, and there are many options to operationalize it. It can be reduced to a simple table, placing the information range into rows and columns. For example, the columns 'type, category and the subcategory of stream' in conjunction with 'output from/input to NBS' applied to the rows 'biomass' and 'living organisms' give a good overview on the material flows and their possible circularities within the sector of urban farming (Canet-Martí et al., 2021). Resources are required or produced during operation and maintenance of NBS, input and output (I/O) streams need to be defined, and there is a gap between potential users and providers of resources (Langegraber et al., 2021a). To solve this problem, a relational database schema can be derived from the streams information model to implement a database, thus improving the resource management in cities.

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4. Papers in the Special Issue "*Water and Circular Cities*"

Table 3 and Table 4 summarised the papers from the Special Issue "*Water and Circular Cities*" in *Water* that are describing the content of Deliverable 3 and that have additionally submitted to the Special Issue, respectively. The six papers from the Special Issue that describe the content of Deliverable 3 in detail (Table 3) can be also found in the Appendix.

Table 3: Papers describing the content of Deliverable 3 (* mark the corresponding author).

Paper	Title	Authors
#1 Framework	A framework for addressing circularity challenges in cities with nature-based solutions	Guenter Langergraber *, Joana A.C. Castellar *, Bernhard Pucher, Gösta F.M. Baganz, Dragan Milosevic, Maria-Beatrice Andreucci, Katharina Kearney, Rocío Pineda-Martos, Nataša Atanasova https://doi.org/10.3390/w13172355
#2 WG1	Closing water cycles in the built environment through nature-based solutions: The contribution of vertical greening systems and green roofs	David Pearlmutter, Bernhard Pucher, Cristina S.C. Calheiros *, Karin A. Hoffmann, Andreas Aicher, Pedro Pinho, Alessandro Stracqualursi, Alisa Korolova, Alma Pobric, Ana Galvão, Ayça Tokuç, Bilge Bas, Dimitra Theochari, Dragan Milosevic, Emanuela Giancola, Gaetano Bertino, Joana A.C. Castellar, Julia Flaszynska, Makbulenur Onur, Marie Carmen Garcia Mateo, Maria Beatrice Andreucci, Maria Milousi, Mariana Fonseca, Sara Di Lonardo, Veronika Gezik, Ulrike Pitha, Thomas Nehls https://doi.org/10.3390/w13162165
#3 WG2	Management of urban waters with Nature-Based Solutions in circular cities	Hasan Volkan Oral *, Matej Radinja, Anacleto Rizzo, Katharina Kearney, Theis Raaschou Andersen, Pawel Krzeminski, Gianluigi Buttiglieri, Derya Ayral Cınar, Joaquim Comas, Magdalena Gajewska, Marco Hartl, David Christian Finger, Jan K. Kazak, H. Mattila, Patricia Vieira, Patrizia Piro, Stefania Anna Palermo, Michele Turco, Behrouz Pirouz, Alexandros I. Stefanakis, Martin Regelsberger, Nadia Ursino, Pedro N. Carvalho * (under review)
#4 WG3	Selected nature-based solutions as building blocks for resource recovery systems in cities	Eric D. van Hullebusch*, A. Bani. M. Carvalho, Z. Cetecioglu, B. de Gusseme, S. Di Lonardo, M. Djolic, M. van Eekert, T. Griessler Bulc, B.Z. Haznedaroglu, D. Istenič, P. Krzeminski, J. Kisser, S. Melita, D. Pavlova, E. Plaza, A. Schoenborn, G. Thomas, M. Vaccari, M. Wirth, M. Hartl, G. Zeeman (under review)
#5 WG4	Nature-based Solutions for Urban Agriculture in Circular Cities: Challenges, Gaps and Opportunities	Alba Canet-Martí, Rocío Pineda-Martos * , Ranka Junge, Katrin Bohn, Teresa A. Paço , Cecilia Delgado, Gitana Alencikiene, Siv Lene Gangenes Skar, Gösta F.M. Baganz https://doi.org/10.3390/w13182565
#6 Summary	Towards a cross-sectoral view on nature-based solutions for enabling circular cities	Guenter Langergraber *, Joana A.C. Castellar, Theis Raaschou Andersen, Maria-Beatrice Andreucci, Gösta F.M. Baganz, Gianluigi Buttiglieri, Alba Canet-Martí, Pedro N. Carvalho, David C. Finger, Tjaša Griessler Bulc, Ranka Junge, Boldizsár Megyesi, Dragan Milosevic, H. Volkan Oral, David Pearlmutter, Rocío Pineda-Martos, Bernhard Pucher, Eric D. van Hullebusch, Nataša Atanasova https://doi.org/10.3390/w13172352

Table 4: Other papers from the Special Issue not related to the deliverable (* mark the corresponding author).

Paper	Title	Authors
#7	Validating Circular Performance Indicators: The interface between Circular Economy and Stakeholders [prepared by Action's WG5]	Chrysanthi-Elisabeth Nika, Alfonso Expósito, Johannes Kisser, Gaetano Bertino, Hasan Volkan Oral, Kaveh Dehghanian, Vasileia Vasilaki, Eleni Iacovidou, Francesco Fatone, Nataša Atanasova, Evina Katsou* https://doi.org/10.3390/w13162198
#8	Causal Relations of Upscaled Urban Aquaponics and the Food-Water-Energy Nexus – a Berlin Case Study	Gösta F.M. Baganz*, Manfred Schrenk, Oliver Körner, Daniela Baganz, Karel J. Keesman, Simon Goddek, Zorina Siscan, Elias Baganz, Alexandra Doernberg, Hendrik Monsees, Thomas Nehls, Werner Kloas, Frank Lohrberg https://doi.org/10.3390/w13152029
#9	Tools for edible cities: A review of tools for planning and assessing edible nature-based solutions	Eric Mino*, Josep Pueyo-Ros, Mateja Škerjanec, Joana A. Castellar, Andre Viljoen, Darja Istenič, Nataša Atanasova, Katrin Bohn, Joaquim Comas https://doi.org/10.3390/w13172366
#10	Rainwater use for vertical greenery systems: Development of a conceptual model for a better understanding of processes and influencing factors	Flora Prenner, Bernhard Pucher*, Irene Zluwa, Ulrike Pitha, Guenter Langergraber https://doi.org/10.3390/w13131860
#11	Application of multi-criteria decision-making tools for assessing biogas plants: a case study in Reykjavik, Iceland	Tamara Llano*, Elena Dosal, Johannes Lindorfer, and David C. Finger https://doi.org/10.3390/w13162150
#12	Impact of green roofs and vertical greenery systems on surface runoff quality	Imane Hachoumi, Bernhard Pucher, Elisabetta DeVito-Francesco, Flora Prenner, Ertl Thomas, Guenter Langergraber, Maria Fürhacker, Roza Allabashi* https://doi.org/10.3390/w13192609
#13	Practical performance and user acceptance of novel dual-flush vacuum toilets	Daniel Todt*, Iemke Bisschops, Paraschos Chatzopoulos, Miriam H.A. van Eekert https://doi.org/10.3390/w13162228

Appendix - Papers from the Special Issue "*Water and Circular Cities*" describing the content of Deliverable 3 in detail

water

MDPI

Article

A Framework for Addressing Circularity Challenges in Cities with Nature-Based Solutions

Guenter Langergraber [1,*,†], Joana A. C. Castellar [2,3,†], Bernhard Pucher [1], Gösta F. M. Baganz [4,5], Dragan Milosevic [6], Maria-Beatrice Andreucci [7], Katharina Kearney [1], Rocío Pineda-Martos [8] and Nataša Atanasova [9]

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Abstract: A novel framework is presented that aims to guide practitioners and decision makers toward a better understanding of the role of nature-based solutions (NBS) in the enhancement of resources management in cities, and the mainstreaming of NBS in the urban fabric. Existing frameworks describing the use of NBS to address urban challenges do not specifically consider circularity challenges. Thus, the new framework provides the following: (1) a comprehensive set of Urban Circularity Challenges (UCCs); (2) a set of more than fifty NBS units and NBS interventions thoroughly assessed in terms of their potential to address UCCs; and (3) an analysis of input and output resource streams, which are both required for and produced during operation of NBS. The new framework aims to facilitate the coupling of individual NBS units and NBS interventions with NBS that enable circular economy solutions.

Keywords: water; resources management; circularity challenges; circular cities

1. Introduction

Despite significant efforts to become more sustainable in managing their resources, cities still represent a big burden to the environment. As the urban population grows, so does the demand for new resources (water, food, energy, materials), coupled with high levels of pollution and ecosystems degradation. Climate change impacts exacerbate the existing environmental problems. Many cities have adopted strategies for sustainable development and a sensible use of resources, e.g., Amsterdam, Copenhagen, Rotterdam [1,2], but unfortunately, the reality is that the majority of cities still follows the typical linear urban metabolism, causing a huge environmental footprint.

In pursuit of sustainability, cities are increasingly putting nature-based solutions (NBS) in the spotlight because of their high potential to address several urban challenges related to resources management in cities such as climate adaptation and mitigation, sustainable consumption and production, air quality, and water management [3–5]. In this work, we use the definition of the COST Action CA17133 Circular City [6] whereby NBS are defined as "concepts that bring nature into cities and those that are derived from nature. . . . As such, within this definition we achieve resource recovery using organisms (e.g., microbes, algae, plants, insects, and worms) as the principal agents. However, physical and chemical processes can be included for recovery of resources, as they may be needed for supporting and enhancing the performance of NBS".

There are several frameworks assessing urban challenges and how they can be effectively addressed by NBS [3,4,7,8]. However, very few existing frameworks put forward urban challenges from the perspective of enhancing the circularity of resources management in cities and ensuring a sustainable urban development. While the framework from the EKLIPSE report [3,4] and the International Union for Conservation of Nature [7] identifies a series of general urban challenges mainly focused on societal, economic, and environmental urban challenges targeted by NBS, the Nature4Cities framework [9] fosters a set of urban challenges that embraces circularity topics in terms of the potential of NBS to promote resource efficiency (e.g., food, energy and water, raw materials, waste, recycling) and green economy (e.g., circular economy, bioeconomy activities, direct economic value of NBS). While this Nature4Cities framework is very valuable in terms of establishing much needed order in a burgeoning field, we believe there is room for the development of a comprehensive list of Urban Circularity Challenges (UCCs) in line with the detailed description of how and to which extent NBS can address such challenges.

Therefore, this research is aimed at narrowing down the list of relevant urban challenges and the interrelations between these frameworks while retaining the necessary information and level of complexity to adequately address the circularity issues at hand. For this purpose, we employ the concept of circular economy (CE), i.e., the circular management of resources in cities through the deployment of NBS. CE has three core principles [10]: (i) the first principle, 'regenerate natural capital', ensures functional environmental flows and stocks, by reducing the use of resources, preserving and enhancing ecosystems, and ensuring minimal disruptions from human interactions and use; (ii) the second principle of 'keep resources in use' is to close material loops and minimize energy loss within the system, which is achieved by optimizing resource yields, optimizing energy and resource extraction, and maximizing their recycling and reuse; and (iii) the third principle, 'design out waste externalities', focuses on the reduction and the residual waste of the system, including economic efficiency. The costs of reducing waste by one unit should be equal to the economic and environmental benefits of having one fewer unit of waste [10,11]. Circularity is viewed here as a strategic approach that helps cities shift from a linear to a circular metabolism, i.e., cities that thrive without demanding too many resources and/or producing waste [12,13] by the implementation of a circular framework for the design and operation of NBS in cities.

Therefore, we propose a framework for addressing UCCs with NBS, which aims to guide practitioners and decision makers toward a better understanding of the role of NBS in the enhancement of resources management in cities and the mainstreaming of NBS in the urban setting. The framework includes the following: (1) a comprehensive set of UCCs based on gaps identified in existing frameworks as proposed by [14]; (2) a set of more than fifty NBS units and interventions (NBS_u/i) assessed in terms of their potential to address UCCs and classified according to the following categories proposed by [15]: nature-based solutions units (NBS_u) defined as "stand-alone green technologies or green urban spaces, which can be combined with other solutions (nature-based or not)" and NBS interventions (NBS_i) defined as "the act of intervening in existing ecosystems and in NBS_u, by applying techniques to support natural processes". This list also includes several Supporting units (S_u) that are required to create CE through NBS; and (3) a systematic approach for defining input and output (I/O) resource streams to and from NBS units/interventions that support creating CE through NBS. Such conceptual and empirical advancement is crucial in order to support the transition from current linear design paradigms to a more circular one when dealing with NBS in urban settlements.

2. Materials and Methods

2.1. A Novel Set of Urban Circularity Challenges (UCCs)

The existing urban challenges frameworks developed by EKLIPSE and Nature4Cities related to resource efficiency [3,4,9] were the starting point for identifying the UCCs used in this study [14]. When it comes to CE and the circular management of resources, a more specific targeted approach is required, and hence, the challenges are defined in a more detailed manner. The issues identified are mostly related to resources management according to the CE principles set by the Ellen MacArthur Foundation [10], namely 'regenerate natural capital', 'keep resources in use', and 'design out waste externalities'.

Implementing these principles for the management of resources in cities would enable an urban transition to circularity. The two obvious challenges for this achievement are [14]:

1. How to minimize the import and consumption of new resources; and
2. How to minimize waste production.

Considering four vital resources, i.e., water, food, energy, and materials, a series of workshops with expert groups were held to break down the two major challenges into a feasible set of challenges related to the observed resources, and for implementing circular resources management in cities. The expert groups are interdisciplinary, and they include a diverse set of professionals and researchers ranging from civil, sanitary, and environmental engineers, architects, urban and landscape planners, natural scientists, agronomists, social scientists, etc. These experts make up the members of the five individual working groups (WGs) formed within the COST Action Circular City (https://circular-city.eu/ (accessed on 30 June 2021)): Built Environment (WG1), Sustainable Urban Water Utilization (WG2), Resource Recovery (WG3), Urban Farming (WG4), and Transformation Tools (WG5).

2.2. List of Nature-Based Solutions (NBS) Units and Interventions (NBS_u/i) for Addressing Urban Circularity Challenges (UCCs)

Implementing NBS for addressing circularity challenges requires the coupling of several units and/or interventions. The list of NBS_u/i addressing UCCs offers a systematic approach for defining the terminology related to and the classification of NBS. A list of thirty-two NBS_u/i proposed by Castellar et al. [15] was used in this study as a baseline for defining the set of NBS for addressing UCCs [14]. The development of the baseline list of thirty-two NBS included a comprehensive analysis of more than two hundred NBS described by four European Horizon 2020 projects: Urban GreenUP (https://www.urbangreenup.eu/ (accessed on 30 June 2021)), UNaLab (https://unalab.eu/en (accessed on 30 June 2021)), Nature4Cities (https://www.nature4cities.eu/ (accessed on 30 June 2021)), and ThinkNature (https://www.think-nature.eu/ (accessed on 30 June 2021)); coupled with mixed quantitative–qualitative approaches such as dedicated workshops, interviews with experts and surveys (for more details concerning the methodology, please consult [15]).

Next, a series of five elicitation workshops adapted from the IDEA ("investigate", "discuss", "estimate", and "aggregate") protocol [16,17] were carried out between June and December 2020 in order to achieve the following: (i) refine the list of NBS, and thus, provide a comprehensive list of NBS for addressing UCCs; (ii) evaluate the NBS according to their ability to address the UCC; and (iii) categorize the NBS. The elicitation workshops were prepared under the scope of the COST Action Circular City and brought together—in each workshop—more than sixty NBS experts with wide and diverse backgrounds (i.e., urban planners, architects, engineers, researchers, social scientists, etc.) from more than thirty countries. The following methodology was applied during the five elicitation workshops:

(i) Development of NBS list: The baseline list of thirty-two NBS_u/i [15] and new NBS_u/i proposed by participants of the workshops were evaluated according to the following eligibility criteria. First, in order to properly cover the scope of the current research, i.e., NBS for resources circularity in cities, the NBS should be in line with the definition of NBS proposed under the COST Action Circular City [6], which in contrast to existing definitions [7,18–21] "transfers the NBS concept into urban areas, putting a special emphasis on resource circularity" [15]. Additionally, physical and chemical processes/technologies for supporting NBS and enhancing their performance have been included as Supporting units (S_u). Second, to avoid duplication issues, the new NBS_u/i proposed by participants must not already be contained in the baseline list of thirty-two NBS_u/i, for example in the case of an already featured unit being listed under a different name. Finally, NBS_u/i should address at least one of the identified UCCs [14];

(ii) Evaluation of NBS potential to address UCCs: To assess the fulfillment of the final eligibility criterion, a special session was conducted, in which a qualitative evaluation of the NBS_u/i that had been selected up until that point was performed. Experts were divided into the COST Action's WGs to discuss the potential of each NBS_u/i for addressing the identified UCCs. They were asked to decide by means of consensus to which degree a given NBS contributes to the achievement of a particular UCC. A four-point scale with respective criteria was defined to represent the degree of contribution to the UCC: (1) the NBS_u/i fully addresses the UCC (score = 1); (2) the NBS_u/i contributes to managing/overcoming the challenge (Score = 0.67); (3) the NBS_u/i—depending on the design—has the potential to contribute to overcoming a given UCC (Score = 0.33); and (4) the NBS_u/i does not address the UCC (Score = 0.0). If it was determined that a particular NBS_u/i failed to address any of the UCCs, it was excluded from the list. To assess the ability of NBS_u/i to address UCCs, we calculated the following global scores: the "UCC global score" is computed by a simple averaging of the NBS_u/i scores for each UCC, and the "NBS global score" is computed by a simple averaging of the UCC scores for each NBS_u/i. Additionally, we counted the number of NBS related to each UCC and the number of UCCs related to each NBS_u/i.

(iii) NBS classification: The resulting set of selected NBS_u/i was classified according to the two categories [15]: NBS_u, which includes NBS spatial units (NBS_su) and NBS technological units (NBS_tu); and NBS_i, which includes NBS soil and river interventions (NBS_is and NBS_ir). As mentioned above, S_u were considered in addition to the classification scheme described here [15]. Next, NBS_u/i including S_u were clustered into sub-categories based on similar technical features, characteristics, and properties for their design, implementation, and functioning in line with their specific purposes. Finally, in further sessions, participants refined the descriptions and nomenclature, and they suggested synonyms for the selected NBS_u/i according to existing standards and literature.

2.3. Nature-Based Solutions (NBS) Circularity: Input and Output (I/O) Streams

In order to overcome the existing deficiencies in urban resource management through the use of NBS in cities, their input and output (I/O) streams need to be defined [22]. Resources required, used, or produced during the operation and maintenance of NBS were identified by a consortium of experts, which included participants from all WGs of the COST Action Circular City. The identification and data collection were done in two stages. In stage one, each WG individually addressed the NBS recognized as relevant to their respective WG. The collection and definition of I/O followed a disciplinary approach, whereby each individual NBS was analyzed based on the state of the art of the individual field of application. The approach was grounded in the need to identify the I/O necessary for operation and maintenance, and the selection was based on physical, chemical, and biological properties. In the second stage, experts from all WGs collaborated in grouping the assembled I/Os into streams [22]. This stage was intentionally conceived to cut across all disciplines (WGs) in order to eliminate the disciplinary bias from step one.

3. Results and Discussion

3.1. Urban Circularity Challenges (UCCs)

The UCCs identified by [14] for shifting to circular management of resources with NBS (Figure 1) are as follows:

- UCC_1: Restoring and maintaining the water cycle;
- UCC_2: Water and waste treatment, recovery and reuse;
- UCC_3: Nutrient recovery and reuse;
- UCC_4: Material recovery and reuse,
- UCC_5: Food and biomass production;
- UCC_6: Energy efficiency and recovery; and
- UCC_7: Building system recovery.

During the participatory approaches carried out in the scope of the COST Action Circular City (see Section 2.1), the UCCs were refined. As a result, detailed descriptions for each UCC as well as the role of NBS_u/i (NBS_u/i) in addressing such challenges are presented in Table A1.

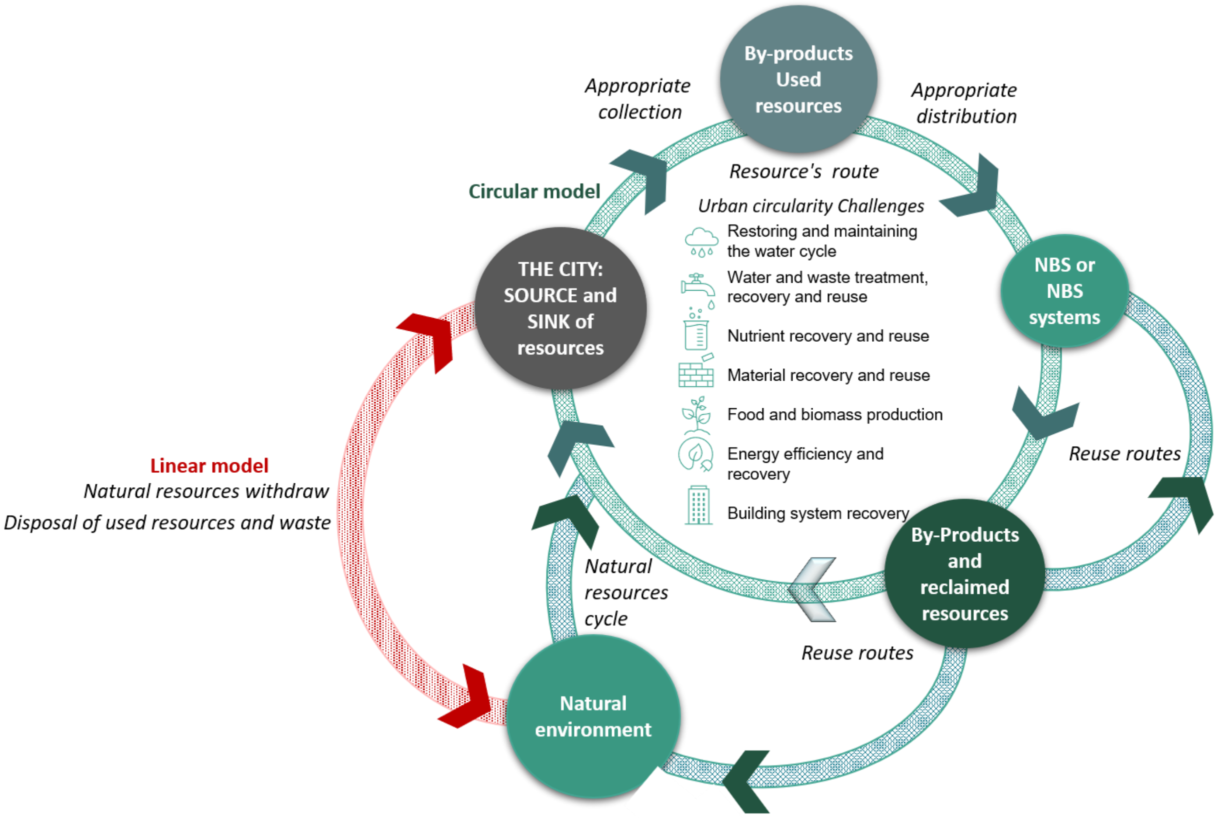

Figure 1. Urban circularity challenges addressed by NBS implemented under a circular framework (adapted from [14]).

The societal challenges addressed by NBS are numerous, ranging from resource recovery to climate change mitigation, ecosystem restoration, and many more. Widespread and successive implementation of NBS will help in climate regulation, both on a micro and macro scale. Considering the limited space in urban areas and the competition for use of open spaces, it is of great importance to focus on providing NBS that contribute to resolving the widest possible range of the above-listed challenges. By implementing NBS in a purposeful way, with multifunctionality and interdisciplinarity in mind, a broader contribution can be made toward achieving a circular management of limited resources. This will also provide economic benefits, as the implementation of multipurpose NBS over single-purpose NBS frees up financial and material resources to be used elsewhere. It is important to ensure cooperation at all stages of NBS implementation, between engineers, architects, landscape planners, politicians, end-users, and any other stakeholder party that is willing and interested to be a part of the discussion. A concerted effort for the broad involvement of stakeholder groups, iterative co-design and implementation processes, and effective communication strategies should be emphasized.

3.2. List of Nature-Based Solutions Units and Interventions for Addressing Urban Circularity Challenges (UCCs)

Resulting from a series of elicitation workshops, we propose a comprehensive list of fifty-one NBS_u and NBS_i, and ten S_u for addressing the UCCs proposed by [14]. During the process, the following three NBS_u/i listed in Castellar et al. [15] were excluded, as they do not address any of the UCCs: "Create and preserve habitats and shelters for biodiversity", "Heritage garden", and "Use of pre-existing vegetation". Moreover, we propose a set of sub-categories for NBS that facilitates the understanding of implicit, but sometimes subtle, relations between the purpose of NBS and some specific requirements concerning technical features for design and implementation.

During the workshops, we determined that the purpose of an NBS_u/i can be related to the technological role/main application goal (e.g., urban rainwater management or food and biomass production), to their greening role at different scales (e.g., public green spaces or vertical greening systems and green roofs) or to their practical application (e.g., soil and water bioengineering). These interrelations were used as bases to cluster the NBS (Figure 2). The resulting NBS sub-categories are described below:

- *Rainwater Management:* This sub-category contains all NBS for rainwater management. These NBS (mainly NBS_tu) are also known as sustainable urban drainage systems (SUDS), low impact development (LID), best management practices (BMPs), water-sensitive urban design (WSUD), etc. [23]. They enable stormwater management, increased infiltration, removal of pollutants, improved quality of runoff, mitigation of flash floods, increased biodiversity, and reduced urban heat island effect;
- *Vertical Greening Systems and Green Roofs:* This sub-category contains NBS_tu for the main types of vertical greening and green roofs. These NBS increase urban biodiversity, decrease the urban heat island effect, improve stormwater management, lower energy consumption, reduce noise, improve air quality, and provide relaxation and socialization areas;
- *Remediation, Treatment, and Recovery:* This group features NBS_u and NBS_i for remediation, treatment, and recovery, and it includes a high number of S_u. These S_u might be a particular requirement for the recovery of resources;
- *(River) Restoration:* This sub-category includes a set of NBS_i related to techniques for river restoration aimed at reducing flood risk and erosion, increasing channel storage capacity, redirecting the water flow, and improving the diversity of riverine species;
- *Soil and Water Bioengineering:* This sub-category includes a set of NBS_i related to soil and water bioengineering techniques. Such NBS_i enhance soil quality, increase carbon storage, decrease soil compaction, minimize/prevent soil erosion, and enhance riverbank protection and hillside stabilization;
- *(Public) Green Space:* This sub-category includes NBS_su that are mainly larger in size and aimed at renaturing cities, controlling urban sprawl, providing niches for urban wildlife and recreational areas for citizens, controlling stormwater, improving air quality, and increasing urban biodiversity; and
- *Food and Biomass Production:* This sub-category comprises NBS_tu and NBS_su for food and biomass production. Additionally, these technologies can generate income, decrease the use of resources and space, and enhance community building.

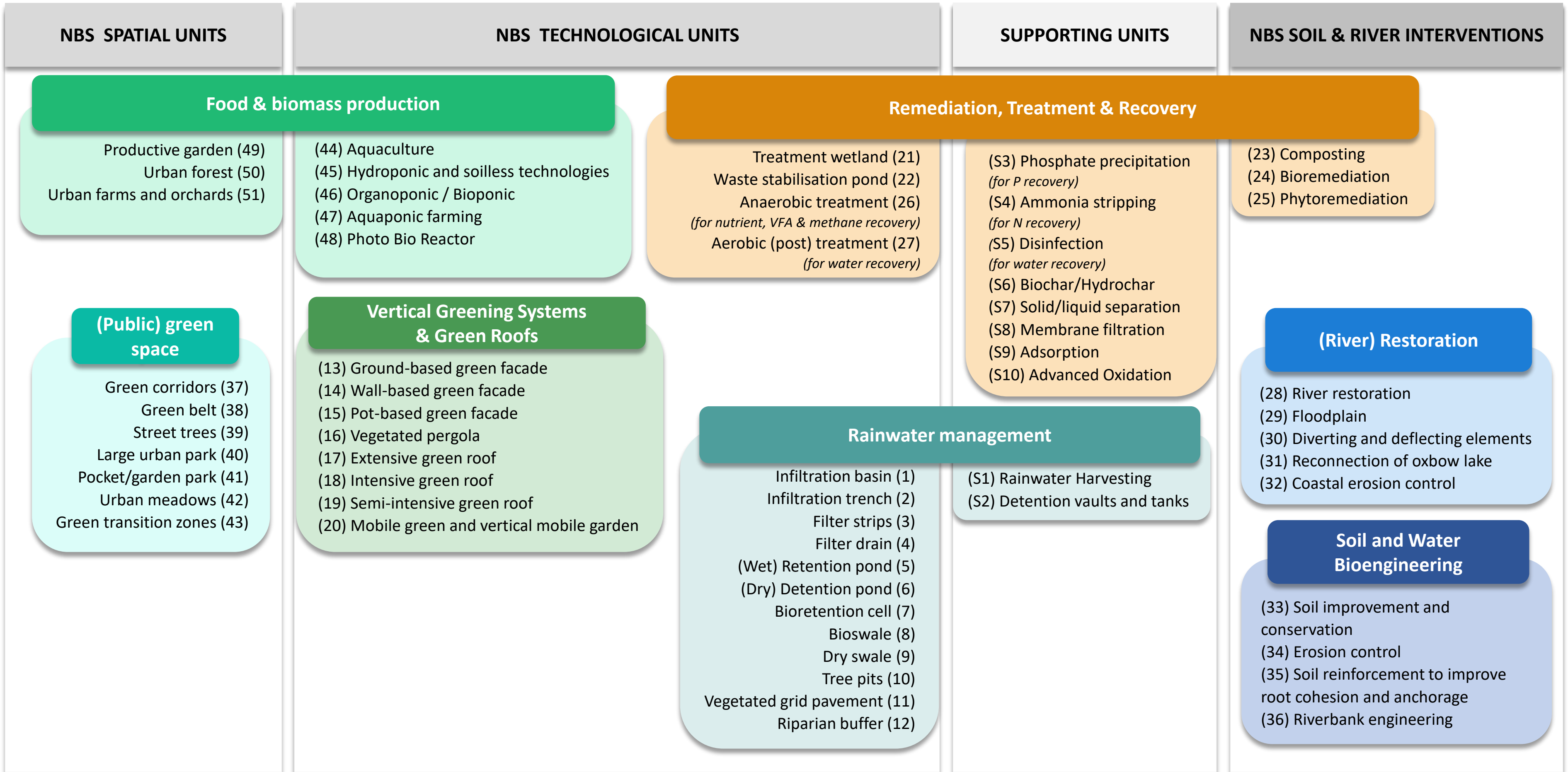

Figure 2. NBS units (NBS_u), NBS interventions (NBS_i), and Supporting units (S_u) clustered into categories (dark gray squares, adapted from [15] and sub-categories proposed by consulted experts within the COST Action Circular City (colored squares).

The presented categories are conceptually fine-tuned and concise enough to guide practitioners and experts in better understanding and assessing the role and relevance of individual NBS in the urban environment. Thus, it may facilitate the selection of the most suitable NBS units and interventions for specific needs and expectations. Moreover, the criteria used to classify the NBS are consistent, setting the proposed classification scheme apart from previous classification attempts [24–27] that are mostly based on hierarchical structures. The above-presented classification scheme adds value by cutting across different category levels, which is a feature that reflects the transversality and multifunctionality of NBS. For example, "Productive garden" and "Aquaponic farming" are both NBS from the "*Food and biomass production*" sub-category, but the former was considered as an NBS_su and the latter as a NBS_tu. The same is true for "Treatment wetland" and "Composting", both NBS are considered to be part of sub-category "*Remediation, Treatment, and Recovery*"; however, the former is an NBS_tu and the latter is a soil intervention (NBS_is). Moving forward, the NBS_u, NBS_i, and S_u for addressing UCCs are sorted according to the sub-categories (described above) and presented in Figure 2 (synonyms and descriptions of NBS_u/i are provided in the Appendix A Table A2).

UCCs addressed by NBS_u/i and S_u are summarized in Table 1. From Table 1, it can be inferred that most NBS_u/i and S_u fully address the UCC_1 ("Restoring and maintaining water cycle"), and UCC_2 ("Water and waste treatment, recovery, and reuse"), while they address UCC_3 ("Nutrient recovery and reuse"), and UCC_4 ("Material recovery and reuse") the least. In addition, WG experts found that the NBS contributions toward overcoming circularity challenges is most evident for UCC_5 ("Food and biomass production"), while the potential contributions of NBS—depending on the design—are considered highest for UCC_4 ("Material recovery and reuse"). The potential is also apparent for further addressing UCC_6 ("Energy efficiency and recovery"), and UCC_7 ("Building system recovery"), as most NBS do not yet fully address them. At the level of individual NBS_u, experts recognized that semi-intensive green roofs, urban farms and orchards, and intensive green roofs contribute the most to solving the recognized UCC. Conversely, diverting and deflecting elements, soil reinforcement to improve root cohesion and anchorage, and coastal erosion control interventions were identified as contributing the least to resolving the UCC. These results indicate the need for further improvement of NBS, especially in order to address the challenges related to nutrient and material recovery and reuse (UCC_3 and UCC_4) in urban areas, which are currently covered least by available solutions.

"*Restoring and maintaining the water cycle*" (UCC_1), "*Water and waste treatment, recovery, and reuse*" (UCC_2), and "*Food and biomass production*" (UCC_5) received the highest UCC global scores: 0.77, 0.68, and 0.53, respectively (Figure 3). Moreover, almost all NBS_u/i were considered to have an impact on water-related UCC_1 and UCC_2, and approximately 78% of all NBS_u/i can address "*Food/biomass-related issues*" (UCC_5). Indeed, almost all NBS_u/i addressing food and biomass production also address water-related challenges, except for NBS such as "Aquaculture", "Composting", and "(River) restoration". This result highlights the multifunctionality of NBS as well as their great potential to restore the water cycle, promote water recovery and reuse, and, at the same time, provide food and biomass in urban settlements (e.g., "Aquaponic farming"). In contrast, the UCC "*Material recovery and reuse*" (UCC_4) received the lowest UCC global score, and only 18 NBS_u/i were related to this challenge. The above-described results indicate that the "circularity" frame of NBS is more explicit regarding the goal of keeping natural resources in use, as is the case with water and biomass. This fact might be explained by the way that NBS_u/i inherently function, in the sense that all NBS_u/i need water to function, and they produce biomass as an output. In contrast, the recovery and reuse of materials is not something intrinsic/vital to the design or functioning of NBS. On the contrary, this approach pushes the conventional design linear frame to move toward a more circular framework in terms of the management of material flows (input and outputs), thus encouraging the consideration of potential interactions between NBS_u/i and their surrounding environment, either by reusing/recovering material from local urban production chains (local INPUTs) or by providing valuable materials as, for example, organic compost to be used by urban farmers (local OUPUT).

Table 1. Urban Circularity Challenges (UCCs) addressed by NBS units (NBS_u), NBS interventions (NBS_i), and Supporting units (S_u) (● = addressing the challenge; • = contribution to challenge mitigation; ○ = potential contribution, depending on the design; and as an "empty cell" = not addressing the challenge). NBS_tu = technological units; NBS_su = spatial units; NBS_is = interventions; NBS_ir = river interventions; and S_u = Supporting unit.

			Urban Circularity Challenge						
Classification		**(#) NBS Units, NBS Interventions, and Supporting Units**	**Restoring and Maintaining the Water Cycle**	**Water and Waste Treatment, Recovery and Reuse**	**Nutrient Recovery and Reuse**	**Material Recovery and Reuse**	**Food and Biomass Production**	**Energy Efficiency and Recovery**	**Building System Recovery**
Rainwater Management	*NBS_tu*	(1) **Infiltration basin**	●	•			○	○	
		(2) **Infiltration trench**	●	○					
		(3) **Filter strips**	●	•					
		(4) **Filter drain**	●	•					
		(5) **(Wet) Retention pond**	●	•		○	○		
		(6) **(Dry) Detention pond**	●	•					
		(7) **Bioretention cell**	●	●	●	○	○		●
		(8) **Bioswale**	●	●			○		
		(9) **Dry swale**	●	○			○		
		(10) **Tree pits**	●	●	●		○	●	
		(11) **Vegetated grid pavement**	●	•			○	●	
		(12) **Riparian buffer**	●	●	●		•	○	
	S_u	(S1) **Rainwater harvesting**	●	○				●	○
		(S2) **Detention vaults and tanks**	●	○					●
Vertical Greening Systems & Green Roofs	*NBS_tu*	(13) **Ground-based green facade**	•	●			•	●	●
		(14) **Wall-based green facade**	●	●	○	○	●	●	●
		(15) **Pot-based green facade**	●	●	○		●	●	
		(16) **Vegetated pergola**	○	●		○	●	●	
		(17) **Extensive green roof**	●	○			●	●	●
		(18) **Intensive green roof**	●	●	○	○	●	●	●
		(19) **Semi-intensive green roof**	●	●	●	○	●	●	●
		(20) **Mobile green and vertical mobile garden**	○	●			•	○	
Remediation, Treatment & Recovery	*NBS_tu*	(21) **Treatment wetland**	●	●	○	○	•	●	○
		(22) **Waste stabilization pond**	●	●					
		(26) **Anaerobic treatment**	●	●	●	○		●	
		(27) **Aerobic (post) treatment**	●	●					
	NBS_is	(23) **Composting**			●	●	●	●	
		(24) **Bioremediation**	○	○		○			○
		(25) **Phytoremediation**	○	○	○	○	•		○

Table 1. *Cont.*

Classification		(#) NBS Units, NBS Interventions, and Supporting Units	Urban Circularity Challenge: Restoring and Maintaining the Water Cycle	Water and Waste Treatment, Recovery and Reuse	Nutrient Recovery and Reuse	Material Recovery and Reuse	Food and Biomass Production	Energy Efficiency and Recovery	Building System Recovery
Remediation, Treatment & Recovery	*S_u*	(S3) **Phosphate precipitation** (for P recovery)	•	•	•				
		(S4) **Ammonia stripping** (for N recovery)	•	•	•				
		(S5) **Disinfection** (for water recovery)	•	•					•
		(S6) **Biochar/Hydrochar production**	•	•		•	•		
		(S7) **Physical unit operations for solid/liquid separation**	•	•		•	·		•
		(S8) **Membrane filtration**	•	•		•			•
		(S9) **Adsorption**	•	•	○	○			
		(S10) **Advanced Oxidation Processes**	•	•					
(River) Restoration	*NBS_ir*	(28) **River restoration**	•	·			·		
		(29) **Floodplain**	•	·			·		
		(30) **Diverting and deflecting elements**	○						
		(31) **Reconnection of oxbow lake**	•	·					
		(32) **Coastal erosion control**	·				○		
Soil & Water Bioengineering	*NBS_is*	(33) **Soil improvement and conservation**	○	○	•	•	·		•
		(34) **Erosion control**	○	○	•		○		○
		(35) **Soil reinforcement to improve root cohesion and anchorage**	○						○
		(36) **Riverbank engineering**	○	○			○		
(Public) Green Space	*NBS_su*	(37) **Green corridors**	•	•			·		
		(38) **Green belt**	•	•			·		○
		(39) **Street trees**	•	•		○	·		○
		(40) **Large urban park**	•	•		○	·	○	○
		(41) **Pocket/garden park**	•	•		○	·	○	○
		(42) **Urban meadows**	•	•		○	·		○
		(43) **Green transition zones**	·	•		○	·	○	○
Food & Biomass Production	*NBS_tu*	(44) **Aquaculture**		○			•	○	•
		(45) **Hydroponic and soilless technologies**	○	○			•	○	•
		(46) **Organoponic/Bioponic**	○	○	•		•	○	•
		(47) **Aquaponic farming**	○	·			•	○	•
		(48) **Photo Bio Reactor**	·	·	•	○	•	•	
	NBS_su	(49) **Productive garden**	•	•	○		•	•	○
		(50) **Urban forest**	•	○			•	•	•
		(51) **Urban farms and orchards**	•	•	•		•	○	•

The NBS global score for all NBS_u/i is shown in Figure 4. All NBS_u/i scores ranged between 0.05 and 0.80. Such an "extreme" range indicates that some NBS_u/i might be very generally applicable and address multiple UCCs, while other NBS_u/i might be more specific and address only a small number of UCCs. In this sense, approximately 40% of all NBS_u/i scored higher than 0.5, thus demonstrating good overall performance in addressing several UCC. The majority of NBS_u/i from "Food and biomass production" and "Vertical greening systems and green roofs" revealed high scores, varying from 0.57 to 0.81, showing that these NBS_u/i tend to be more versatile and generalist (address well multiple UCCs). Whereas NBS_u/i from "(River) Restoration", "Soil and Water Bioengineering" to "Rainwater management" might be better suited for addressing specific UCCs, since the majority of NBS_u/i from these sub-categories had low scores, varying between 0.05 and 0.33. In fact, as expected, all NBS from these subcategories scored for water related UCC_1 and UCC_2. It should be noted that no NBS_u/i from these sub-categories addressed all seven UCCs, and only eight NBS_u/i (out of 21) addressed more than four UCCs.

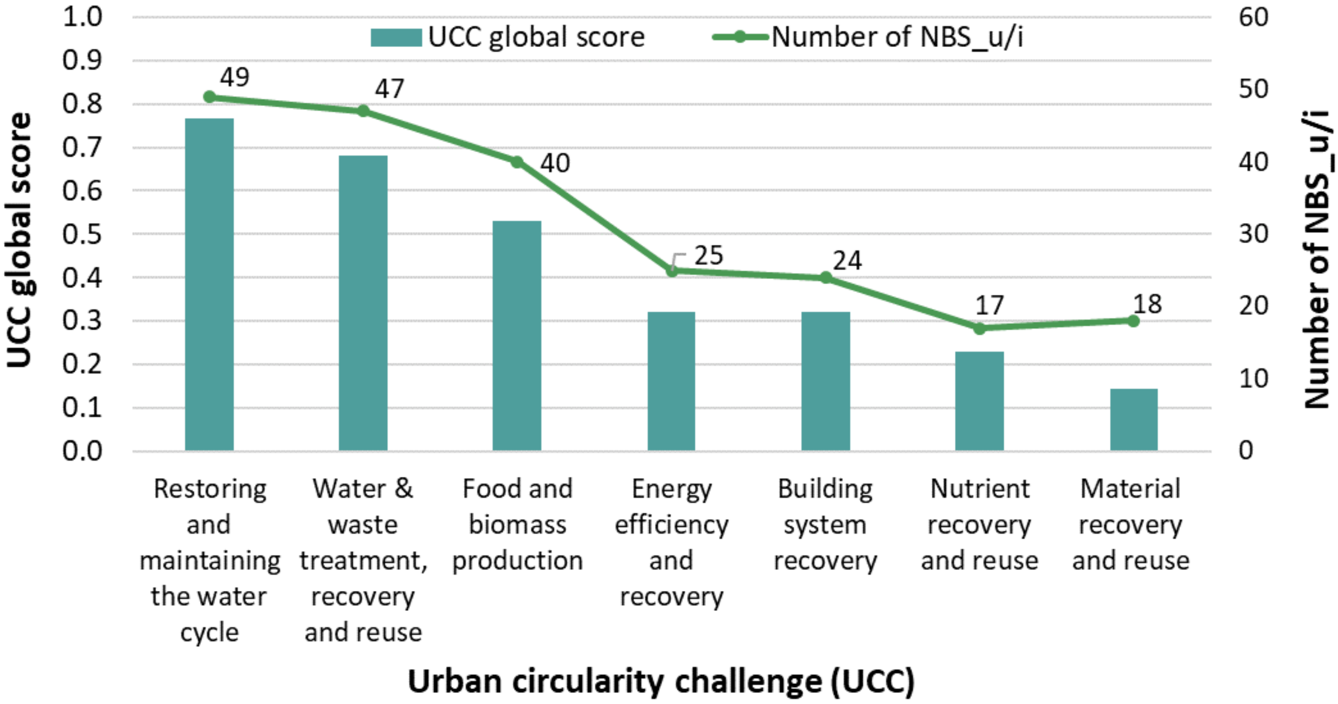

Figure 3. Performance of NSB_u/i in addressing Urban Circularity Challenges.

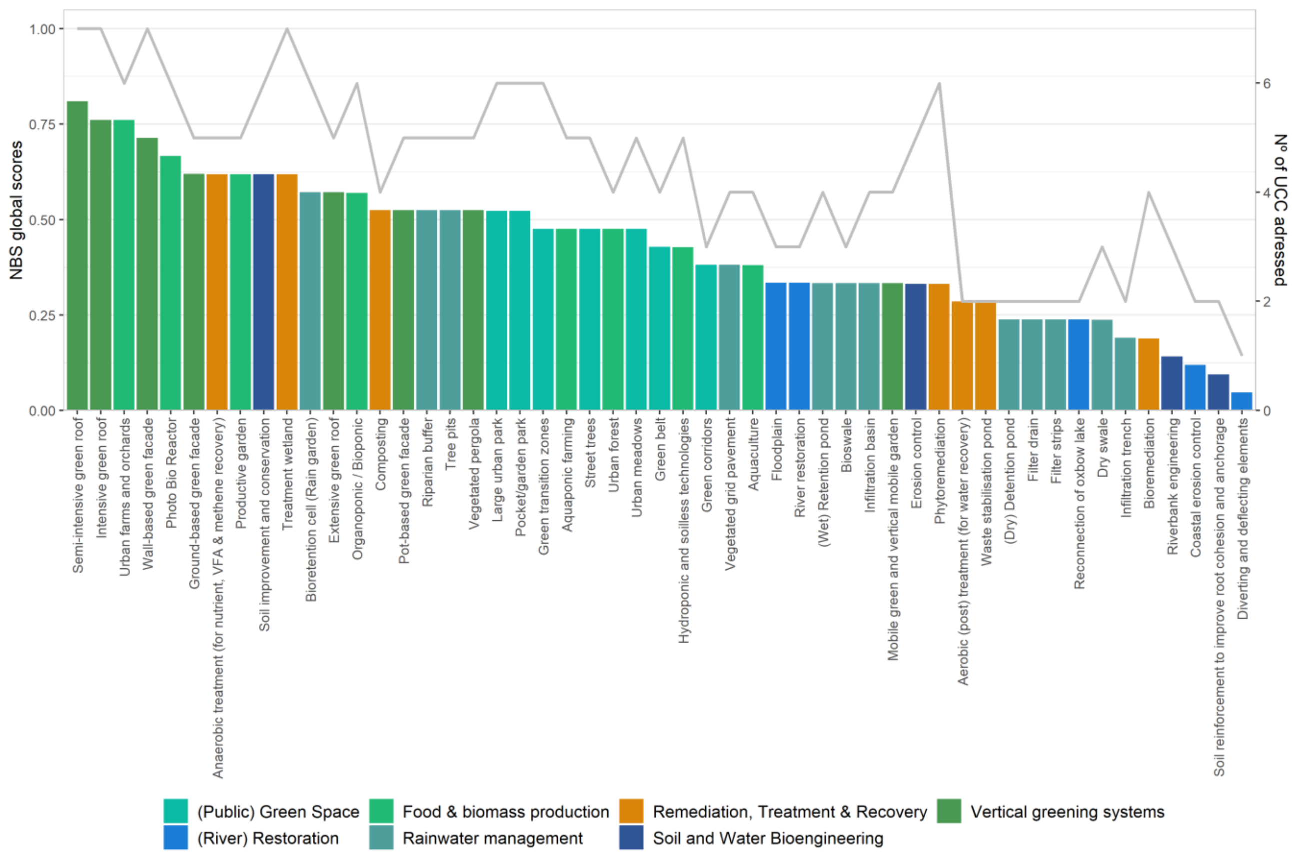

Figure 4. NBS global scores for UCC (colored bars) and number of UCC addressed per each NBS_u/i (gray line). Obs: The bars are colored as a function of pre-established sub-categories.

3.3. Nature-Based Solutions' (NBS) Circularity: An Analysis of Inputs (I) and Outputs (O)

In this article, Inputs (I) required for operation and maintenance of NBS_u/i and S_u and potential Outputs (O) produced by NBS_u/i and S_u are considered as streams (elements and resources flowing through NBS). As inputs, these streams are required for the operation and maintenance of NBS, and thus, they can come from or be produced by other NBS or from other parts of the urban system. As outputs, the streams present resources to be recovered and provided for holistically operating NBS in circular cities, and thus, they are essentially produced by NBS and can flow to other NBS or to other parts of the urban production chain. In the course of the elicitation workshops, five streams were identified (water, nutrients, biomass, living organisms, and energy), comprising over 20 categories (Figure 5).

Figure 5. Main types of streams and respective categories of inputs required for the operation and maintenance of NBS and/or outputs potentially produced by NBS in circular cities.

Understanding the role of NBS in optimizing the flow of different streams is a very important step to promote their implementation for circular cities. However, an equally important aspect is the potential interactions between streams that can be expedited through the implementation of NBS in cities. Streams and their respective categories as shown in Figure 5 are described below:

- *Water:* NBS can play an important role in establishing a more efficient and more circular management of water streams in urban settlements. Moreover, all plant-based systems, such as NBS, rely on a sufficient water supply to permit their full multifunctional properties. The stream categorisation is based on the main elements of urban water management. Precipitation and surface runoff are key categories in urban water management. Precipitation can be directly used as an input without the need for human interference and should be considered for assessing potential hydric deficits that may need to be compensated by other water streams. Surface runoff is generated by precipitation falling onto sealed areas (e.g., roofs, streets) and thus requires retention, transportation, treatment, and storage for reuse. However, the management of surface runoff using NBS [23] follows the conventions of urban drainage where the primary focus lies in removing water from the city as quickly as possible. This way of thinking needs to be reformed by CE concepts to foster a culture of reuse. Wastewater is a valuable but often overlooked water stream. While wastewater in the urban environment is mainly thought of as originating from domestic or industrial activities, specific NBS can also be a source of wastewater (i.e., aquaculture or urban farms), meaning this category can be represented as either an input or an output. The main concerns surrounding the flow of wastewater streams in the urban context are the potential health risks related to reuse practices as well as bureaucratic burdens (i.e., permissions), a lack of common agreement regarding reuse standards required for various different final uses, and structural requirements for practices such as source separation (graywater and blackwater). Even though these concerns are valid, scientific research has demonstrated that the collection of graywater followed by on-site treatment using NBS can present a valuable source of non-potable water [28].

- *Nutrients:* Nutrients can be categorized as solid, liquid, or gaseous. Their management is linked to managing water and biomass streams. The recovery of nutrients from the wastewater stream also promotes the practice of decentralized source separation. While graywater plays an important role in ensuring sufficient water quantity, black water presents a source of nutrients for various uses [29]. An important factor for the recovery of specific nutrients is the S_u in Table A2. An often overlooked fact is the introduction of nutrients via the atmosphere [30].
- *Biomass and living organisms:* Biomass and living organisms are streams related to NBS_u/i associated with urban agriculture and the establishment of an interconnected, sustainable urban food system. Biomass includes categories such as organic fertilizer (compost, manure), organic crop protection products, soil conditioners (mulch, woodchips, or biochar), and a wide range of organic wastes (food waste, crop residues, or pruning remains). Living organisms are the backbone of urban agriculture because they are either prerequisites for food production or constitute food themselves, from plants to vertebrates and microorganisms. Biomass and living organisms can be inputs as well as outputs of various NBS_u/i for urban agriculture and thus have high potential to contribute to circularity in the city. Parts of both streams cross the circular city system boundary, for agriculture and aquaculture are sectors where economies of scale are significant and often cannot be fully exploited by NBS_u/i for urban agriculture due to space constraints in cities. Another reason for this is the need for an external NBS_u/i due to specialization, e.g., the need for fish hatchery rearing fingerlings used in urban aquaponics.
- *Energy:* Energy production and energy savings are key aspects of NBS. While the shading, cooling, and insulation effects can lower the energy demand of a building, source separation, as discussed with the water stream, can provide energy in the form of biogas. Heat exchange from graywater or wastewater has also been identified as an important potential source of energy in circular economies.

To illustrate the interaction of streams, one can analyze the potential of building integrated NBS_u, namely green roofs and pot-based green facades. At the building scale, source separation is generally applicable. By using a two-pipe system, graywater (wastewater without toilet waste) can be captured, and its heat energy can be extracted by heat exchange technology. For water reuse, either green roofs or pot-based green facades can act as treatment units [28]. The supplied water for treatment also acts as a driver for transpiration cooling by the plants. Treated graywater can be used further for irrigation, toilet flushing, and other applications. The wastewater from the toilet can be treated on-site by using S_u, namely an anaerobic reactor producing nutrient-rich effluent and biogas while also eliminating pathogens and rendering water fit for reuse. Further treatment of the effluent is possible by green roof or pot-based facade systems, which themselves support cooling, biodiversity, and biomass production when harvested, and, as previously discussed, have a high energy-saving potential.

4. Conclusions

The following can be concluded:

- The unique list of thirty-nine NBS units, twelve NBS interventions, and ten Supporting units was specifically developed for addressing the Urban Circularity Challenges (UCCs).
- The list of NBS units and interventions (NBS_u/i) is presented in a concise way including categorization, clear nomenclature, and descriptions.
- By including the series of workshops within the COST Action Circular City, the list of NBS_u/i was developed in an interdisciplinary setting intended to facilitate their widespread application.

- The sub-categories applied in the grouping of NBS_u/i according to their main application/role allow for easy understanding and application of the list.
- The framework model combining NBS_u/i with UCCs, with versatile urban sectoral applications, enables the promotion and implementation of innovative plans of action with inclusive and relevant urban regeneration solutions, understanding urban demands as transformative target opportunities toward a resource-efficient and holistic growth model.
- It is noteworthy that the majority of NBS_u/i and S_u from the compiled list are able to fully address the challenges related to the water cycle restoration and maintenance (UCC_1), as well as the treatment, recovery, and reuse of water and waste in cities (UCC_2). In contrast, the current ability of NBS to address the recovery and reuse of nutrients (UCC_3) and materials (UCC_4) in urban areas is still limited (according to the involved experts' knowledge and experience) and requires further research.
- The systematic methodology applied for defining input and output streams facilitates the integration of NBS_u/i into circular solutions and fosters circular thinking.

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Appendix A

Table A1. Descriptions of Urban Circularity Challenges.

Urban Circularity Challenge	Description
UCC_1—"Restoring and maintaining the water cycle"	UCC_1 relates to the water cycle and, more specifically, includes the objective of restoring the natural, pre-development water cycle (mainly by rainwater management). This refers to the behavior of water entering the urban system as precipitation, and the proportions that respectively contribute to evapotranspiration, infiltration, runoff, and other hydrological processes that characterize the water balance. Greening of the urban environment, reducing the proportion of impervious surfaces, rainwater harvesting, and preserving soil and wetlands for water storage all contribute to slowing the passage of water throughout the catchment and help to re-establish a near pre-development water balance. By implementing NBS throughout urban areas, it creates a web of dispersed facilities for onsite stormwater management and runoff control through temporal storage, infiltration, and groundwater recharge. In this context, protection against floods and drought constitutes the central benefits relating to the other challenges [31–33]. The NBS that address this challenge include various infiltration options such as retention ponds, green roofs, rain gardens, and floodplains.

Table A1. *Cont.*

Urban Circularity Challenge	Description
UCC_2—"Water and waste treatment, recovery, and reuse"	UCC_2 embraces topics and potential issues to be addressed by NBS in the scope of water and wastewater treatment, recovery, and reuse. The treatment of wastewater removes pollutants that can be damaging to the environment and sensitive ecosystems as well as pose health risks to urban dwellers. Instead of conventional practices of collecting all streams of used water in underground pipes and conveying it to a centralized wastewater treatment plant, circularity involves more differentiated management of the various wastewater streams from industry and households. The wastewater streams (i.e., gray, yellow, brown, black) can be reused in a fit-for-purpose approach, in which the quantity and quality of the water that is to be reused should match the quality requirements of the reuse purpose. NBS central to treatment, recovery, and reuse of water include treatment wetlands, rain gardens, or rain-harvesting systems [34,35].
UCC_3—"Nutrient recovery and reuse"	UCC_3 focuses on the recovery and reuse of nitrogen (N), phosphorus (P), and potassium (K), which are valuable resources that enter household wastewater through human excreta. Removal of these components from wastewater not only ensures a safer reintroduction into the natural environment, but these components also serve as a resource in fertilizer production, which can be utilized in urban agriculture or landscaping. The separation of different substance streams is an efficient way to recover nutrients such as N and P, but this practice requires substantial changes in the way we manage human waste. Substantial changes to infrastructure at both household and city level are needed for the source separation approach. Nutrients recovered from wastewater streams and source separation can be used in gardening and food production as a circular alternative to artificial fertilizers. Struvite fertilizer is an example of nutrient recovery for food production [29,36]. Using the nutrients from wastewater is not a new concept, but the systematic implementation of such practices and adjusting city planning accordingly is. The NBS central to nutrient recovery and reuse include treatment wetlands, waste stabilization ponds, composting, bioremediation, and phytoremediation.
UCC_4—"Material recovery and reuse"	UCC_4 embraces topics related to material recovery and reuse, and it pertains to the resources needed in the built environment. The concept of an urban mine relates to the idea that there is already an abundance of materials present in the urban environment that can be repurposed, recycled, and reused instead of relying on primary resources imported from outside the city. Extending this concept to NBS, some of the urban greening measures such as urban parks and urban meadows can provide biomass for various uses, such as insulating material or other bio-based materials used in construction and manufacturing processes. Biochar production was identified as a supporting NBS_u in the Circular City repository that can supply a high-energy, renewable energy source from plant material.
UCC_5—"Food and biomass production"	**UCC_5** relates to the crucial matter of sustainable food and biomass production in cities. Since there is no food production without water, the many intersections between urban water and urban agriculture are clear as well as the intrinsic link between UCC_5 and water-related $UCC_{1,2}$. For example, NBS such as hydroponic systems are generally more efficient than traditional soil-based systems in terms of water use and can be as productive as the latter. In addition, various types of water sources (from tap water to wastewater) can be collected and recirculated within the hydroponic system. Noteworthy NBS used in urban agriculture are ground-based and rooftop gardens, edible walls, hydroponic food production (indoor and outdoor), as well as urban orchards, honey production, and aquaculture. However, NBS with different purposes (beyond food production) can interact in order to address UCC_5 and other linked $UCC_{1,2,3}$. For example, treatment wetlands (TWs) used for water pollution control can contribute to a community garden through the provision of treated wastewater for irrigation and the production of compost or peat, which can be used for conditioning soils, boosting soil fertility, increasing water storage capacity, and improving productivity [37].
UCC_6—"Energy efficiency and recovery"	Reducing the demand for imported (fossil fuel-based) energy is the main challenge from a CE viewpoint related to energy. Energy-efficient buildings, mitigation of the urban heat island effect—and consequently, reducing the demand for cooling in buildings—and heat and energy recovery from different waste streams are foreseen goals that can be achieved with NBS in a circular concept [14].
UCC_7—"Building system recovery"	UCC_7 relates to the topic of regeneration of the built environment, i.e., architecture and infrastructure for living, working, manufacturing, and developing other activities. The construction materials and building systems are exposed to less weathering, such as snow, rain, wind, and extreme temperatures. Buildings and open spaces are shaded from UV radiation and pollutants, which increases the lifespan of most common building materials and reduces the rate at which renovations or the replacement of infrastructure have to take place [38]. In turn, this can save resources that often rely heavily on the use of fossil fuels and other non-renewable resources. Greening the open space and implementing water-sensitive urban design are equally key strategies, aimed at providing ecosystem services related to water, such as stormwater management, and on-site water reuse, as well as, indirectly, urban heat island mitigation.

Table A2. Descriptions and synonyms/subgroups of NBS units (NBS_u), NBS interventions (NBS_i), and Supporting units (S_u) from Table 1.

#	Units/Interventions	Synonyms/Subgroups	Descriptions
1	**Infiltration basin**	Green water storage and infiltration system; Storm basin; Non-permanent infiltration basin; Green water storage and infiltration system; Storm basin; Micro-catchment; The sponge zone [15]	An **infiltration basin** is a surface storage basin designed for short-term temporal water storage by using an existing natural depression in the ground or by creating a new one. After a heavy rain, the water fills up the depression. Then, the water soaks into the ground or drains to the sewage system. If there is no heavy rainfall, the area is dry and could be used as a green area. Adapted from [15].
2	**Infiltration trench**	Percolation trench	**Infiltration trenches** are laminated systems with fabric-lined excavations atop a fabric-lined reservoir to increase infiltration. Adapted from [39].
3	**Filter strips**	Vegetative filter strips	A **filter strip** is a sloped medium that attenuates stormwater runoff by converting it into sheet flow and is typically located parallel to an impervious surface such as a parking lot, driveway, or roadway. Furthermore, the adoption of vegetated filter strips is increasing as they have been demonstrated to be effective for trapping runoff and sediment and promoting soil infiltration. Adapted from [39,40].
4	**Filter drain**	Filter trench; Surface sand filter	**Filter drains** are shallow trenches filled with stone/gravel that create temporary subsurface storage for attenuation, conveyance, and filtration of surface water runoff. The stone may be contained in a simple trench lined with a geotextile, geomembrane, or other impermeable liner, or with a more structural facility such as a concrete trough. Adapted from [41].
5	**(Wet) Retention pond**	(Wet) Retention basin; Wet pond; Wet pool; Water retention ponds; Green retention pond; Extended Retention Basin; Holding pond; Pond; (Wet) retention basin [15]	**(Wet) Retention ponds** consist of a permanent lagoon area with landscaped banks and surroundings to provide additional storage capacity during rainfall events. It has the capacity to continuously retain storm water, remove urban pollutants, and improve the quality of both surface runoff and release this at a controlled rate. During dry periods it also holds water. Adapted from [15].
6	**(Dry) Detention pond**	(Dry) Detention basin; Dry ponds	**Detention ponds**, or dry ponds, are stormwater basins designed to intercept stormwater runoff for temporary impoundment and metered discharge to a conveyance system or a receiving waterbody. In this regard, it can contribute to the prevention of urban flash flooding. Adapted from [39].
7	**Bioretention cell**	Bioretention facility; Rain garden; Pluvial beds; Biofilter; Infiltration/stormwater planters; Infiltration garden; Rainfall garden; Water control garden, Floodable garden, Bioretention filter, Bioretention area, Bioremediation wet retention [15]	A **bioretention cell** is a shallow depressed vegetated area that primarily serves as a small-scale water control (storage and infiltration) area, especially in cities. It is designed to collect, store, filter, and treat water runoff. Storm water runoff is drained, stored for a certain period, and then, it infiltrates either into the ground soil or flows into the sewage system. To optimize its functions, it must include a porous soil mixture, native vegetation, and some hyper accumulator plants, which are capable of phytoremediation. Adapted from [15].

Table A2. *Cont.*

#	Units/Interventions	Synonyms/Subgroups	Descriptions
8	**Bioswale**	Swale; Green drainage corridor; Vegetative filter; Vegetated bioswale [15]	A **bioswale** is a vegetated, linear, and low-sloped shallow pit or channel, often established in urban areas. It is designed to store and convey surface water runoff and also to remove pollutants and sediments. Furthermore, vegetation can intercept rainfall, increase subsurface water storage capacity, and improve infiltration. This NBS is often used to drain roads, paths, or car parks while enhancing access corridors or other open space. Adapted from [15,42].
9	**Dry swale**	Grassed swale	A **dry swale**, or grassed swale, is an open vegetated conveyance channel that filters, attenuates, and detains stormwater runoff as it moves downstream. Vegetation can include turf, meadow grasses, shrubs, and small trees (in limited quantities). Furthermore, the water flow through the swale can be slowed by a series of check dams. Adapted from [39,43].
10	**Tree pits**	Planters; Tree box; Tree pit filter	**Trees pits** and planters can be designed to collect and attenuate runoff by providing additional storage within the underlying structure. The soils around trees can also be used to directly filter out pollutant from runoff. (SUDS Manual). A tree box filter or in-ground well consists of a container filled with amended soil and planted with a tree, which is underlain by crushed gravel media. Tree pits are attractive for stormwater control in dense urban areas because of their small size, low cost, and associated co-benefits that they bring by greening the streets. Adapted from [39,41,44].
11	**Vegetated grid pavement**	Permeable/pervious/infiltration pavements; Green/greened/vegetated/grass pavements; Green parking pavements; Engineered vegetated green pavement; Grass block paver/interlocking grass paver; Permeable pavements and parking lots; Pervious surfacing; Permeable green pavements [15]	A **vegetated grid pavement** includes planted pavement structures normally filled with soil, grass seeds, gravel, or rocks. It can be considered as a type of pervious/permeable pavement. The runoff soaks through the pavement structure and can be stored or infiltrated into the ground. Accordingly, using permeable pavement is appropriate for decreasing the urban flooding problem and urban heat island effect. The structures are modular and adaptable to different surface types such as parking areas, roadways, cycle–pedestrian paths, sidewalks, or street furniture zones. Usually, the costs and maintenance are low compared to traditional pavements. Adapted from [15,45].
12	**Riparian buffer**	Riparian buffer strip; Vegetative filter strips; Buffer strips	A **riparian buffer** reduces surface runoff and detains sediments and sediment-bound pollutants from (mainly) agricultural areas. Located between agricultural catchments and streams/rivers, they act as filters for pollutants and sediment transportation into the river, slowing down the flow. They comprise hydric soil with facultative vegetation along the banks of a river or stream offering niche ecotone services. Riparian buffers provide a series of ecosystem services and functions such as reservoirs of biodiversity, flood mitigation, wetland products, bank protection, recreation, and water purification. Adapted from [39,46].

Table A2. *Cont.*

#	Units/Interventions	Synonyms/Subgroups	Descriptions
13	**Ground-based green facade**	*Green facade*; Green facade with climbing plants; Climber green wall; Ground-based green-wall; Green climber wall; Green wall with ground-based greening; Climber plant wall; Ground-based green facade with climbing plants; Soil-based green façade [15]	A **ground-based green facade** is a wall completely or partially covered with greenery. The climber plants are planted in the ground (soil, technical, or recycling substrates) or in containers (filled with soil) and grow directly on the wall, or climb using climbing-aids (e.g., on a frame) that is connected to the wall. These NBS can also be implemented along highly frequented roads to reduce noise emissions. Adapted from [15].
14	**Wall-based green facade**	*Green wall;* Hydroponic green facade; Facade-bound greening; Facade bound green wall; Living wall; Continuous green wall; Plant wall system; Green façade with vertical panels; Greening vertical panel; Vertical greening panel [15]	A **wall-based green facade** (or green wall) comprises panels and technical structures (3D frames filled with technical substrate) that are seeded or planted. These panels and structures are fixed onto facades or walls or can be designed as stand-alone system and allow the placement of plants and substrate on the entire surface. Some systems allow the removal of panels during winter time. Compared to soil/ground-based green facades a wider plant range can be applied for wall-based green facades. Adapted from [15].
15	**Pot-based green facade**	Living wall; Planter green wall; Planter green facade; Planter boxes; Planter pots; Planter-based green wall; Planted/planting container(s); Pot planted plants; Potted plants; Potted mobile garden; Raised bed; Container plants [15]	A **pot-based green facade** involves the use of planted containers such as pots or planters, filled with artificial (technical) soilless substrate or soil or a mixture. They can be placed on the ground or directly on the building or balconies. They can be used with almost any kind of plants, e.g., climbing plants, trees, and/or shrubs. Adapted from [15].
16	**Vegetated pergola**	Green pergola; Greened pergola; Green mattresses; Green shady structures; Green shade [15]	A **vegetated pergola** uses pillars, beams, stretched textile structure, and lattices in different materials and compositions to create a growing assistance for vegetation and provide shaded areas. On this structure, an inert substrate can be installed, to be covered with seeds. Vegetated pergolas can be fixed to the facades of the buildings, on the street, or by posts fixed to the sidewalk. Adapted from [15].
17	**Extensive green roof**	Green roof; Vegetated roof; Living roof [15]	An **extensive green roof** implies basic, light-weight, planted systems that are implemented on the rooftop of a building. The most common plants used are sedum, herbs, mosses, and grasses. The installation and maintenance are less expensive than that of intensive systems. The substrate is relatively thinner (10–15 cm, or reduced form >10 cm) than for intensive systems (more than 20 cm). Adapted from [15].
18	**Intensive green roof**	Green roof; Roof garden; Roof park; Vegetated roof; Living roof; Public intensive green roof; Social intensive green roof [15]	An **intensive green roof** consists of vegetation (higher variety than extensive green roof) that are installed on rooftops, normally accessible for public or recreation or gardening, relaxation, and socialization purposes. This NBS is usually heavier and has a deeper substrate (more than 20 cm) as compared to extensive systems. In addition, it requires more installation and maintenance effort such as regular irrigation and fertilization, but it provides more biotopes and higher biodiversity. Adapted from [15].

Table A2. *Cont.*

#	Units/Interventions	Synonyms/Subgroups	Descriptions
19	**Semi-intensive green roof**	Green roof; Smart roof; Vegetated roof; Living roof; Biodiversity roof; Eco systemic roof [15]	A **semi-intensive green roof** is a combination of areas as intensive and extensive green roof. It is implemented on rooftops and is characterized by small herbaceous plants, ground covers, grasses, perennials and small shrubs, as well as higher growing plants, requiring moderate maintenance. The recommended minimum substrate thickness is between 12 cm (grass or herbaceous plants) and 20 cm (smaller shrubs and coppices), but it can be adjusted. This type of green roof has higher maintenance than extensive systems and has the potential to host a richer ecology. Adapted from [15,47].
20	**Mobile green and vertical mobile garden**	Mobile vertical greening; Mobile green living room; Mobile green wall; Mobile vertical garden; Portable green wall; Mobile planter [15]	These NBS units are mobile and thus can be located anywhere in the city. A **mobile green** is usually organized as greened or planted containers or pots that are removable. All plant types can be used for this NBS. For trees, large-scale containers are required. A **vertical mobile garden** is a vertical, mobile, planted, self-supporting module. It is fixed to a hook lift container platform. On this structure, different layers are placed along a substrate (also hydroponic can be used) in which the plants can grow. Adapted from [15].
21	**Treatment wetland**	Constructed wetland; Reed bed; Planted horizontal/vertical filters; Helophyte filter; Root-zone wastewater treatment; Natural wastewater treatment; Artificial wetland; Planted sand/soil filters [15]	**Treatment wetlands (TWs)** include a range of engineered systems designed and constructed to replicate natural processes occurring in natural wetlands involving vegetation, soils, and the associated microbial assemblages to assist in treating wastewater streams (e.g., domestic wastewater, graywater, industrial wastewater) and stormwater. TWs can be divided in two main hydrological categories: **Free water surface wetlands**, a shallow sealed basin or sequence of basins (open water areas) containing floating plants, submerged plants, or emergent plants (similar in appearance to natural marshes); Subsurface flow wetlands, which include **Horizontal flow (HF) wetlands** and **Vertical flow (VF) wetlands**. In this case, the water flows beneath the surface level, either horizontally or vertically, through the filter bed. Adapted from [15,48].
22	**Waste stabilization pond**	Wastewater pond	**Waste stabilization ponds (WSPs)** are earthen ponds designed and constructed in series, where sequential microbial metabolisms (anaerobic + facultative + aerobic) are established. WSPs utilize both physical and biological processes to remove organic materials, pollutants, and pathogens in raw wastewater. The size of the infrastructure can be comparable to a treatment wetland unit in some cases, and it can be applied also for cities. Adapted from [49,50].
23	**Composting**	Community composting; Compost heap; Composting facility [15]	**Composting** includes all the structures and procedures required to compost food waste, vegetable materials, waste from cleaning grain, crop residues, etc. Adapted from [15].

Table A2. *Cont.*

#	Units/Interventions	Synonyms/Subgroups	Descriptions
24	**Bioremediation**		**Bioremediation** refers to bacteria- and fungi-based techniques to remediate contaminated soil and groundwater while simultaneously improving soil quality and providing ecosystem services. Bioremediation approaches can be applied in situ or ex situ, which depends on the nature of contaminant and site conditions. Adapted from [51,52].
25	**Phytoremediation**		**Phytoremediation** refers to plant-based techniques to remediate contaminated soil and groundwater while simultaneously improving soil quality and providing ecosystem services. Phytoremediation is a cost effective, non-intrusive, and aesthetically pleasing technology that removes contaminants by applying processes and mechanisms of degradation, sequestration, or transformation. Adapted from [53,54].
26	**Anaerobic treatment** (for nutrient, VFA, and methane recovery)		**Anaerobic treatment** refers to a treatment technology that stabilizes organic wastes or organic pollutants in wastewater, without the need for aeration. During anaerobic treatment, biodegradable organic compounds are mineralized, leaving inorganic compounds such as NH4+, PO43-, HS- in the solution. Anaerobic treatment can be conducted in technically plain systems, and the process can be applied at any scale and at almost any place. During treatment, useful energy in the form of biogas (CH_4 and CO_2) or chemical building blocks such as volatile fatty acids (VFA) are produced. Adapted from [55].
27	**Aerobic (post) treatment** (for water recovery)		**Aerobic treatment** refers to the removal of pollutant under the presence of dissolved oxygen. In aerobic biological oxidation reactors, the conversion of organic matter is carried out by mixed bacterial cultures in general accordance with the following stoichiometry: COHNS + O_2 + nutrients$\rightarrow$ CO_2 + NH_3 + $C_5H_7NO_2$ (new cells) + other end products. Examples of aerobic reactors are activated sludge and biofilm reactors. Aerobic autotrophic bacteria are responsible for nitrification (conversion of ammonium to nitrate) in these reactors. Adapted from [56].
28	**River restoration**	River re-naturing; River revitalization; Blue corridors; Soil-bioengineering for river re-naturing; River restoration; River revitalization; Daylighting; Reopened stream; Channel widening and length extension; Reprofiling the channel cross-section; Channel reprofiling and re-opening; Fluvial restoration/rehabilitation; Deculverting and re-meandering [15]	**River restoration** includes a set of techniques that aim to reduce pluvial flood risk and erosion. The river channel is widened or deepened, recovering part of its former channel, and enhancing the flood dissipation capacity. In case of covered/buried watercourses, the channel can be opened by removing concrete layers. Both ways lead to an increment of storage capacity of the channel and natural development of the riverbed and riparian zone. Adapted from [15].

Table A2. *Cont.*

#	Units/Interventions	Synonyms/Subgroups	Descriptions
29	**Floodplain**	Reprofiling/extending floodplain; Branches; Floodplain restoration; Floodplain widening; Restore/increase the floodplain area; Room-for-the-river approach/Floodplain management [15]	**Floodplains** aim to reduce flood risk by expanding the flood plain/water retention, thus providing additional flood space. Floodplain can be restored by excavating the lateral riverbed or by dividing the discharge into branches and by-passes, creating islands. During low water levels, these relatively flat and accessible bank areas can be used for multifunctional purposes. Floodplain restoration enables more efficient work of sewer and storm water pipe drainage systems by reducing their operational load and decreasing the need for expensive pipe solutions. Adapted from [15,57].
30	**Diverting and deflecting elements**	Natural flow diversion structures; Redirection of water flow, Stimulation of river dynamic processes; Instream structures; (Soil and) water bioengineering for stream restoration; Water bioengineering flow changing techniques; Riverbed morphology engineering; Increased water course friction [15]	**Diverting and deflecting elements** employ elements such as rocks, larger tree trunks, and willow branches that are placed near the riverbank or in the middle of a river. These interventions alter flow variation and sediment shifting processes, affecting the development of the channel's length and depth. In this sense, the main objective is to redirect, disturb, divert, and deflect the water flow and initiate water dynamics for riverside protection against erosion. Adapted from [15].
31	**Reconnection of oxbow lake**		An oxbow lake is an ancient meander that was cut off from the river, thus creating a small lake with a U-form. **Reconnecting oxbow lake** with the river consists in removing terrestrial lands between both water bodies, therefore favoring the overall functioning of the river by restoring lateral connectivity, diversifying flows, and cleaning the river section of the present oxbow for a better water retention during floods. The reconnection of oxbow lakes is also important for improving the diversity of riverine species. Adapted from [58].
32	**Coastal erosion control**		**Coastal erosion control** summarizes a set of techniques that aim to reduce coastal erosion by reducing wave velocity and trapping sediments. These technologies include coastal wetlands, salt marshes, large woody debris, coral and oyster reef systems, semi-permeable and permeable dams, etc. and techniques for sand dune restoration. Adapted from [59,60].
33	**Soil improvement and conservation**	Soil enhancement; Soil amendment; Soil improvement and conservation measures; Soil enhancement(s); Gentle remediation options; Soil management; Engineered, improved soil [15]	**Soil improvement and conservation** comprise several approaches to maintain and enhance soil quality in terms of physical, chemical, and biological features. It aims to improve nutrient management, increase carbon storage, enhance water infiltration and retention, encourage beneficial soil organisms and prevent soil compaction. Some examples of specific techniques are application of biochar, mulching, use of leguminous species for enhancing nitrogen fixation, use of organic matter, retaining stubble and green manuring to increase organic content and reduce compaction and erosion, and organic fertilizer that stimulate and increase the soil biological activity and diversity. Adapted from [15].

Table A2. *Cont.*

#	Units/Interventions	Synonyms/Subgroups	Descriptions
34	**Erosion control**	Soil bioengineering (slope); Soil (and water) bioengineering for slope stabilization and erosion control; Soil and slope revegetation; Strong slope vegetation; Slope vegetation/revegetation; Slope stabilization through revegetation; Soil and slope stabilization; Vegetation engineering systems for slope erosion control [15]	**Erosion control** includes a set of different soil bioengineering techniques to stabilize soil structure on steepened slopes, to minimize/prevent the erosion of soil from wind or water, landslides, and sedimentation problems. Common techniques are: revegetation (plants with strong deep roots), hydro-seeding, erosion control mat, covering natural fiber mats, wooden structures, and surface roughening. Adapted from [15].
35	**Soil reinforcement to improve root cohesion and anchorage**		**Soil reinforcement to improve root cohesion and anchorage** is induced by using live plant material for engineering purposes: woody plants and parts of plants (branches or stems) are placed in a constructive manner and according to defined design principles, e.g., brush layering, branch packing, live staking, fascine constructions. Furthermore, it is possible to use the construction waste for the reinforcement of soft soil foundation in coastal cities. This approach can decrease the cost of garbage removal and transportation, reduce the cost of foundation reinforcement, and also reduce the land occupation by waste. Adapted [61,62].
36	**Riverbank engineering**	Riverbank engineering; Vegetation engineering systems for riverbank erosion control; Bioengineering (soil, water, fluvial, riverbanks); Riverbank stabilization/slope stabilization; Vegetated bank protection; Systems for erosion control on riverbanks; Riverbank protection system [15]	**Riverbank engineering** techniques are used in fluvial bioengineering for riverbank protection and hillside stabilization to reduce the risk of erosion by generating a natural protection. Some techniques embraced are as follows: planted embankment mat; plants established on hills with strong inclination to provide strong and branched root networks; engineered designs using plant material and woody plant parts (e.g., fascine constructions, willow branch mattress); living and dead wood can be combined (e.g., vegetated crib walls, dead and live wood branch packing) for linear application and wide-spread effects; live stakes and other plant elements can be used jointly or individually to stabilize the slope (live stakes, root stocks, fascine brushes, etc.). Adapted from [15].
37	**Green corridors**	Green way [15]	**Green corridors** aim to renature areas of derelict infrastructure such as railway lines or along waterways and rivers, transforming them into linear parks. This NBS can be considered as a transitional area between biomes that connect neighborhoods. Green corridors can play an important role in urban green infrastructure networks and can offer niche shelter, food, and protection for the urban wildlife to survive and move from one green space patch to another. Adapted from [15].
38	**Green belt**	Green bypass	A **green belt** is a green area surrounding built-up area. It is a planning device designed to contain urban growth that is established for dividing urban and rural areas, and it has the function of supressing urban sprawl and providing recreational areas for residents. Adapted from [63,64].

Table A2. *Cont.*

#	Units/Interventions	Synonyms/Subgroups	Descriptions
39	**Street trees**	Allée; urban trees; Trees on streets; Tree infrastructure; Planting and renewing urban trees; Boulevards; Urban tree canopy; Tree infrastructure; Urban trees alignment; Single line trees; Sustainable management of urban trees; Single tree [15]	**Street trees** are focused on planting, renewing, or maintaining urban street trees. It is designed to be appropriate for its context (right tree in the right place) and to achieve multiple benefits. One single or several trees can be arranged along streets, bicycle paths, and sidewalks. These trees are situated on a single side (e.g., single line trees), and if circumstances allow, they can be established on both sides of the route (e.g., boulevard). In the latter case, the treetops of opposite trees often form a (nearly) closed canopy. Street trees support healthy urban communities through the provision of environmental, social, and economic benefits. They improve cities' liveability through the provision of shade, stormwater reduction, improved air quality, and habitat connectivity for urban fauna. Social benefits are represented by the sense of community and safety, and reduced rates of crime. Regarding economic benefits, street trees can reduce energy costs and also increase the business income and property values Adapted from [15].
40	**Large urban park**	Urban park; Public park; Park; Green park; Residential park; City park; Large urban public park; Greened recreation areas/regional parks; Green resting areas; City park [15] and [65]	**Large urban parks** refers to large green areas (>0.5 ha) within a city with a variety of active and passive recreational facilities that meet the recreational and social needs of the residents and of visitors to the city. They are open to wide-range communities. Large urban parks can serve all the city or part of city, and they are open to a wide range of communities. Adapted from [15].
41	**Pocket/garden park**	Small park; Neighborhood park; Landscape park; Empowerment park; Pocket parks [15] and [65]	**Pocket or garden parks** are publicly accessible and compact green areas or small gardens (<0.5 ha) around and between buildings vegetated by ornamental trees, grass, and other types of plants. The area is projected for resting, relaxation, observing nature, social contact, and physical health. Pocket or garden parks provide opportunities for people to create small but important public spaces left in their own neighbourhoods. Adapted from [15].
42	**Urban meadows**	Urban wildflower meadows	**Urban meadows** are species-rich grasslands created over a longer period of time, which are beneficial to native wildlife in the urban environment. The type of meadow created and method used to create and manage them will vary with conditions, habitat, and budget. The benefits of implementing urban meadows (instead of mown grass in urban public green spaces) are evident for urban biodiversity, human wellbeing, and for local economy as a cost-effective solution. Adapted from [66].

Table A2. *Cont.*

#	Units/Interventions	Synonyms/Subgroups	Descriptions
43	**Green transition zones**		**Green transition zones** are between high vegetation (urban forests and parks mainly) and adjacent areas or infrastructure and embedded in urban environments, functioning as enriching spatial units (ecotones) in the landscape, requiring special(ized) management and providing different spaces, including in quality or extent of NBSs in comparison with bordering spaces or ecosystems. Vegetation transitions, or ecotones, represent border regions of transition between communities, ecosystems, or biomes, that reflect both local and regional changes in abiotic conditions. Adapted from [67,68].
44	**Aquaculture**	Flow-through fish farm; Recirculating Aquaculture Systems (RAS)	**Aquaculture** is the farming of aquatic organisms, including fish, molluscs, crustaceans, and aquatic plants. Farming implies some form of intervention in the rearing process to enhance production, such as regular stocking, feeding, protection from predators, etc. Farming also implies individual or corporate ownership of the stock being cultivated. Aquaculture includes flow-through fish farms as well as recirculating aquaculture systems (RAS). Aquaculture has potential for providing lower priced fish, enhancing nutritional security and employing poor urban communities. Urban aquaculture can decrease the distance between farm and plate, generate income, use less resources, and serve as a community-building tool. Adapted from [69].
45	**Hydroponic and soilless technologies**		**Hydroponics** is an agricultural method that provides soilless plant growth by applying the mixture of water and nutrient solution that is controllable and can be delivered to plants based on their needs. This system provides improved control of plant's nutrition, efficient use of space, and the possibility of saving fertilizers. Greenhouses with hydroponic systems are seen as sustainable systems for growing food in cities with improved control of plant growth. The huge potential offered by this cultivation approach ranges from productive and qualitative advantages to environmental benefits due to higher efficiency in using water and nutritional resources, $NO3-$ management, and crop quality increase. Adapted from [70–72].
46	**Organoponic/Bioponic**		**Organoponic/bioponic** is an emerging soilless technology for nutrients recovery that links organic vegetable production to organic effluent remediation or organic waste recycling (adapted from [73]). Bioponic production describes a contained and controlled growing system in which plants in growing media derive nutrients from natural animal, plant, and mineral substances that are released by the biological activity of microorganisms [74].

Table A2. *Cont.*

#	Units/Interventions	Synonyms/Subgroups	Descriptions
47	**Aquaponic farming**	Aquaponics; Trans-aquaponics	**Aquaponic farming** comprises aquaponics (which couples tank-based animal aquaculture with hydroponics) as well as trans-aquaponics, which includes integrated aqua–agriculture systems exploiting the aquaponic principle without these restrictions. Adapted from [75]
48	**Photo Bio Reactor**		A **Photo Bio Reactor (PBR)** is defined as a closed (or mostly closed) vessel for phototrophic production in which the energy is supplied via electric lights. A PBR design should use light efficiently with uniform illumination, reduce shading, provide a fast mass transfer of CO_2 and O_2, and attain high biomass growth. Adapted from [76,77].
49	**Productive garden**	Market garden; Community garden; Mobile vertical garden (with substrate or soil)	**Productive gardens** are areas of land dedicated to the cultivation of vegetables, fruits (fruit trees), (flowers), and small livestock (chicken) for the main purpose of food production (whose output has a significant share of food production). These gardens can be differently owned, yet ownership has no effect in terms of the function of the NBS unit. Adapted from [15].
50	**Urban forest**	Group of trees; Wood; Urban woodland; Arboreal areas around urban areas; Arboreal urban parks; Arboretum; Urban tree cover [15]	An **urban forest** mimics the appearance/form of a forest in an urban setting. It comprises all woodlands, groups of trees, and individual trees, forests, street trees, trees in parks and gardens, and trees in derelict corners. Usually, urban forests are managed and enable foraging for food. Benefits of urban forests range from psychological, aesthetic, recreational, and health benefits to amelioration of urban climate, mitigation of air pollution, and increased urban biodiversity. Adapted from [15].
51	**Urban farms and orchards**	Small-scale farms	**Urban farms and orchards** are agriculture ventures dedicated to food production in a city; they are often professionally run and considerably larger than gardens. Food production may include big livestock (cows), fruits (fruit trees), and main food crops (maize, wheat). Larger urban farms also participate in community programmes such as skills development and job training that can benefit underserved populations. Furthermore, as a form of green infrastructure, urban farms and community gardens can help reduce urban heat island effects, mitigate the impacts of urban stormwater, and lower the energy embodied in food transportation. Adapted from [78].
S1	**Rain Water Harvesting**		**Rainwater harvesting** (RWH) in cities consists of the concentration, collection, storage, and treatment of rainwater from rooftops, terraces, courtyards, and other impervious surfaces for on-site use, with the aim of reducing drinking water consumption from centrally supplied sources. Rainwater harvesting reduces runoff volume and peak flows. Rainwater can be collected in cisterns, bladder tanks, and precast ferrocement septic tanks. Adapted from [39,79].

Table A2. *Cont.*

#	Units/Interventions	Synonyms/Subgroups	Descriptions
S2	**Detention vaults and tanks**	Wet vaults; Dry vaults; Attenuation storage tanks	**Detention vaults and tanks** are underground storage/treatment facilities constructed of reinforced concrete (vaults) or corrugated pipe (tanks). They may be used to handle general site runoff, or they may be dedicated to the runoff from impervious surfaces such as roofs and parking lots. Detention vaults may be designed to empty completely between storms (dry vaults), or they may be designed to maintain a permanent water pool (wet vaults). These facilities provide runoff volume control, peak discharge reduction, sediment control, and harvesting potential. Adapted from [39].
S3	**Phosphate precipitation** (for P recovery)		**Phosphate precipitation** refers to the chemical precipitation of phosphorus. It is brought about by the addition of the salts of multivalent metal ions that form precipitates of sparingly soluble phosphates. The multivalent metal ions used most commonly are calcium, aluminum, and iron. For struvite precipitation, magnesium is added. Struvite precipitation is controlled by a combination of physicochemical factors including temperature, mixing energy, pH, the degree of Mg, NH4, and PO4 supersaturation, and the presence of competing ions. Magnesium generally needs to be added. Adapted from [56,80].
S4	**Ammonia stripping** (for N recovery)		Gas stripping (such as dissolved ammonia) involves the mass transfer of a gas from the liquid phase to the gas phase. The transfer is accomplished by contacting the liquid containing the gas (ammonia) that is to be stripped with a gas (usually air) that does not contain the gas initially. For **ammonia stripping**, the ammonia stripped from the wastewater is converted to ammonium by passing the off-gas through an acid bath/scrubber. Adapted from [56].
S5	**Disinfection** (for water recovery)		**Disinfection** describes a process that eliminates pathogenic microorganisms the use of chemical agents (such as chlorine and its compounds), physical agents (such as light, heat, and sound), mechanical means, and radiation. Adapted from [56].
S6	**Biochar/Hydrochar production**		**Biochar** is a carbon-rich solid by-product produced through high-temperature pyrolysis or the degasification of organic material under low or no oxygen environment, which prevents combustion. Biochar is being used in an increasing number of fields and has been widely employed in a variety of applications, such as an adsorbent, a source of nutrients, and soil amendment agent where the biochar amendment could further suppress plant diseases as well. Properties of biochar and its applications are highly influenced by the mode of preparation and type of feedstock used. High moisture-containing feedstocks are converted into biochar (hydrochar) with the help of hydrothermal carbonization (HTC). Adapted from [81].

Table A2. *Cont.*

#	Units/Interventions	Synonyms/Subgroups	Descriptions
S7	**Physical unit operations for solid/liquid separation**		**Physical units for solid/liquid separation** mostly used in wastewater treatment are screening, grit removal, sedimentation, high rate clarification, accelerated gravity separation, (bio-) flocculation, and flotation. Adapted from [56].
S8	**Membrane filtration**		During **membrane filtration,** the role of a membrane is to serve as a selective barrier that will allow the passage of certain constituents and will retain other constituents found in the liquid. Adapted from [56].
S9	**Adsorption**		**Adsorption** is the process is the process of accumulating substances that are in solution on a suitable interface. Activated carbon treatment of wastewater is usually thought of as a polishing step, for example for removing micro-pollutants such as pharmaceuticals, personal care products, and hormones. Adapted from [56].
S10	**Advanced Oxidation Processes (AOP)**		**Advanced oxidation processes (AOP)**, such as ozone treatment, are used to oxidize complex organic constituents found in wastewater; they are difficult to degrade biologically (for example micro-pollutants) into simpler end products. Adapted from [56].

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Closing Water Cycles in the Built Environment through Nature-Based Solutions: The Contribution of Vertical Greening Systems and Green Roofs

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Abstract: Water in the city is typically exploited in a linear process, in which most of it is polluted, treated, and discharged; during this process, valuable nutrients are lost in the treatment process instead of being cycled back and used in urban agriculture or green space. The purpose of this paper is to advance a new paradigm to close water cycles in cities via the implementation of nature-based solutions units (NBS_u), with a particular focus on building greening elements, such as green roofs (GRs) and vertical greening systems (VGS). The hypothesis is that such "circular systems" can provide substantial ecosystem services and minimize environmental degradation. Our method is twofold: we first examine these systems from a life-cycle point of view, assessing not only the inputs of conventional and alternative materials, but the ongoing input of water that is required for irrigation. Secondly, the evapotranspiration performance of VGS in Copenhagen, Berlin, Lisbon, Rome, Istanbul, and Tel Aviv, cities with different climatic, architectural, and sociocultural contexts have been simulated using a verticalized ET_0 approach, assessing rainwater runoff and greywater as irrigation resources. The water cycling performance of VGS in the mentioned cities would be sufficient at recycling 44% (Lisbon) to 100% (Berlin, Istanbul) of all accruing rainwater roof–runoff, if water shortages in dry months are bridged by greywater. Then, 27–53% of the greywater accruing in a building could be managed on its greened surface. In conclusion, we address the gaps in the current knowledge and policies identified in the different stages of analyses, such as the lack of comprehensive life cycle assessment studies that quantify the complete "water footprint" of building greening systems.

Keywords: water reuse; water management; water cycle; nature-based solutions; green roofs; vertical greening systems; life-cycle assessment; circular cities; built environment; building greening

1. Introduction

Natural water cycles are under increasing pressure from urban expansion, which is driven by incessant population growth. It is expected that the world's urban population will grow from 3.4 billion people in 2009 to 6.3 billion in 2050. The demand for water will increase by 55%, which will lead to a rise in water pollution, aggravating problems associated with water scarcity [1], since water availability is compromised by its quality [2].

In fact, of all the fresh water entering the city, only a fraction is actually used for consumption; the remaining becomes polluted, treated, and discharged [3]. Within this linear process, valuable nutrients, such as nitrogen and phosphorus, are lost in the treatment process instead of being captured and cycled back (e.g., for agricultural usage or maintenance of green areas) [4]. Stormwater management is another example of this non-sustainable linear water process, as typically, its main goal is the fast discharge of stormwater to avoid flooding. With changes in climate, however, rainfall patterns can exceed the capacity of the sewer system and cause widespread flooding [5]. Under dry conditions, however, in which water would be needed to irrigate and sustain vegetation to maintain its necessary cooling function, water is once again used linearly, with fresh drinking water exploited, as no other source is stored or provided [6].

In this sense, Nature-Based Solutions units (NBS_u) as green technologies that can be implemented in combination with existing infrastructure or as stand-alone systems [7] can support the transition towards a new water reuse paradigm, by integrating circular economy (CE) principles into urban water management.

When implementing urban NBS_u to create "circular cities", the following urban circularity challenges (UCC) [8,9] can be addressed: (i) restoring and maintaining the water cycle (by rainwater management); (ii) water and waste treatment, recovery, and reuse; (iii) nutrient recovery and reuse; (iv) material recovery and reuse; (v) food and biomass production; (vi) energy efficiency and recovery; and (vii) building system recovery. The built environment can be identified as a key facilitator to address, promote, and benefit from a change in the water use paradigm by using the UCC to shift towards a circular management of resources [8]. At the building systems level [10], water streams, including separated wastewater, precipitation, and runoff, can be reused on site using NBS_u and supporting units (e.g., non NBS based on the COST Action CA17133 definition [11]). The same concept can be applied towards green building sites, and further support "reuse" practices in green building materials.

At the building scale, NBS_u, such as vertical greening systems (VGS) (ground-based green facade, wall-based green facades, pot-based green facades, and vegetated pergola) and green roofs (GRs) (intensive, extensive and semi-intensive) can be integrated in the building envelope of new and existing buildings in order to address the listed UCC. The reuse of water and nutrients through source separation at the building level is supported by those NBS_u. Greywater (household wastewater without the toilet stream) has proven to be a viable resource for irrigation, and the necessary treatment can be done by judiciously employing on-site systems, such as pot-based green facades and GRs [12,13]. In addition, water via rainwater harvesting can be reused for irrigation [14].

Plant water consumption must be met throughout the year to allow for the full spectrum of multifunctionality, e.g., increasing biodiversity, contributing toward public health, decreasing air pollution, and cooling the surrounding area [6]. This "demand" is mainly met with fresh water or drinking water, further contributing to water depletion [14]. However, operational water demand is not the only important factor in water reuse practices. NBS_u require resources for their initial production, and the processes used to manufacture their constituent materials are often highly water dependent as well [15]. Moreover, the production chains of components for VGS and GRs not only consume water, but the "production" of this water requires energy for pumping and often for treatment—meaning that carbon emissions are associated with constructed systems such as these, which are conceived as NBS_u, and where the expressed intent is often to reduce a building's environmental footprint.

Transformation of the water use and reuse paradigm is needed in order to reduce fresh water depletion. Therefore, the hypothesis of this work is: "The illustration of the needed water demand for the production of building materials for NBS_u, as well as their operational water needs, will help to foster rethinking towards the implementation of water reuse practices."

In this paper we consider two categories of NBS_u as vehicles for applying CE principles (especially fostering water reuse), surveying the existing knowledge, barriers, and gaps that are crucial for their wider implementation, and for fostering a transition from the existing linear water use paradigm within the built environment. A schematic depiction of this existing linear paradigm is presented in Figure 1.

To support CE principles in the water sector, we first examine the "wicked problem" of urban water management. We then review the relevant literature on selected NBS_u functions, performance, and impact. To provide more detail on their actual water needs, we scrutinized the published studies, which quantified both the materials and irrigation requirements in the context of a life-cycle assessment (LCA).

As the actual water demand of plants is highly dependent on various geographical, climatic, and physiological factors, a case study was used as a methodological approach to simulate the potential for meeting water demand with rainwater and greywater availability in model buildings located in a cross-section of European cities. Finally, we discuss the knowledge gaps and policy barriers that must be overcome to achieve widespread implementation of building greening systems, and offer recommendations to accelerate the use of NBS_u in the built environment, ultimately creating more circular cities.

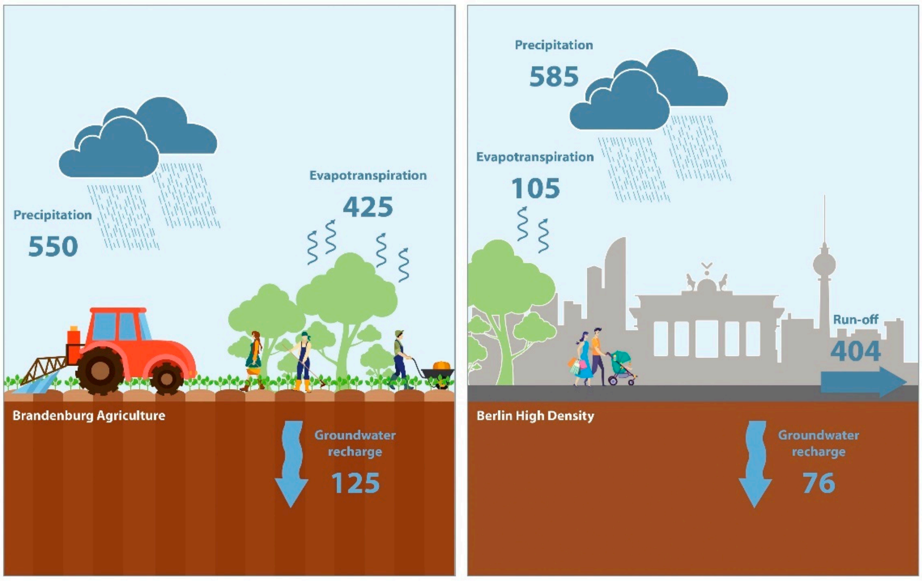


Figure 1. Schematic representation of the mean annual water balance in an agricultural landscape west of Berlin (**left**) and a densely overbuilt quarter with >85% soil sealing in the city of Berlin, Germany (**right**). Drawing based on data available from the state of Brandenburg (www.lfu.brandenburg.de, accessed on 7 October 2021) for the years 1991–2015 (given in mm/a). Illustration: Dimitra Theochari and Thomas Nehls (unauthorized use is not permitted).

This is the first large collaborative European study that (a) conducted a comprehensive, in-depth review of LCA studies that focused particularly on GRs and VGS, with an emphasis on water as an input to the material inventory; and (b) quantitatively compared the water balance of these systems in a range of European cities, with different climatic and cultural attributes.

2. Materials and Methods

2.1. Wicked Problem of Water

Water use, particularly reuse at the city scale, is a complex procedure. Therefore, the term "wicked problem of water" is introduced and described, using several important fields in urban water management. The needed information was gathered based on available literature of the following topics:

- Closing the water cycle at the building scale;
- Embodied energy in the provision of water;
- Technical facilities for greywater treatment at the building scale;
- NBS_u for greywater treatment at the building scale;
- Policies and regulation to support water reuse.

2.2. Green Roofs and Vertical Greenery System Water Use Based on LCA Studies

The impacts embodied by GRs and VGS could be considered in a LCA, which provides a quantitative evaluation of a product or system's environmental impact based on the inventory of materials required to build it. In contrast to typical building components, VGS and GRs are living systems, which rely not only on the materials originally employed in their construction, but on "materials" that must be continuously supplied throughout the building's life, such as water. Hence, a more detailed investigation on the actual water use over the lifespan of a NBS_u can support change toward a more circular water loop. Water usages by GRs and VGS are addressed, based on literature reviews related to LCA studies.

2.3. Simulation Case Study

The aim of this simulation case study was to assess the potential contribution of VGS to the management and recirculation of water—preferably rainwater run-off, but also greywater at the building scale (in an urban context). Therefore, (i) the amount of otherwise drained or wasted water accruing in densely populated city center quarters, with different urban morphologies, was estimated; and (ii) this water "supply" was compared to the water "demand" or water loss, due to evapotranspiration of VGS located in different climatic zones. It is assumed that no storage capacity is provided to use as surplus run-off, or greywater, in subsequent months of a water deficit.

The potential water demand of a generic VGS model system was estimated. Driven by pragmatic curiosity—we calculated the balances between the available water and water demand for typical buildings, in six home cities of the authors, (Table 1).

Table 1. Parameters describing the climatic, architectural, and hydrological characteristics of the case studies. The presented data included precipitation (P), temperature (T), evapotranspiration (ET), greywater (GW) production per inhabitant, occupancy (O) and run-off (RO) generation.

City	Climate [2]					Typical Building					Water Availability		
	Class [1]	*P*	*T*	*P-ET* Oct-Mar	Apr-Sep	Ground	Facade	Window	v/h	*O*	*GW* Capita	*GW* Facade	*RO* Facade
		mm/a	°C	mm		m²			(-)	inh/m²	L/inh d	L/m² d	
Copenhagen	Dfb	614	9.4	151	−206	980	3206	1408	3.27	0.044	51	0.69	0.37
Berlin	Dfb	585	10.3	118	−238	166	440	132	2.65	0.065	63	1.54	0.43
Rome	Csa	605	17.8	135	−644	1302	3996	813	3.07	0.029	90	0.85	0.41
Lisbon	Csa	571	17.4	126	−791	237	407	142	1.72	0.021	81	0.99	0.71
Istanbul	Csa	546	16.0	−18	−840	231	310	132	1.34	0.170	58	7.35	0.82
Tel-Aviv	Csa	506	21.5	−171	−1090	165	330	66	2.00	0.040	58	1.16	0.57

[1] acc. to Köppen-Geiger, [2] acc. to Meteonorm 8, Meteotest Bern, Switzerland 2000–2019.

2.3.1. Calculating Rainwater Run-Off Availability

The building-related rainwater run-off (RO) discussed here was harvested from the roofs. The harvested water was a high proportion of precipitation (P) and the collected water was clean compared to street RO. There are several types of contaminants typical to roofs, such as depositions from the urban atmosphere and substances released from roofing and gutter materials [16]. Most of these contaminants can be discarded using a first flush diverter. Several technical guides for rainwater harvesting suggest a first flush diversion of 0.1 to 1 mm [17,18]. Following these guidelines, a first-flush diversion of 1 mm was considered here in RO calculations on a daily base. RO was calculated by applying the static run-off coefficient (RC) of 0.9 and the ground area of the chosen buildings, assuming that it approximated the roof area well. For P, long-term averages (2000–2019) were taken from the database Meteonorm 8 (Meteotest, Bern, Switzerland) using interpolated data sets for all cities (Table 1).

2.3.2. Estimating Greywater Availability

The greywater availability was calculated based on published greywater production rates for the corresponding countries or cities (Table 1) and the occupancy of the buildings (inh/m^2) related to the ground area of the building. Occupancy (O) was calculated using the average population density per district divided by the fraction of buildings to total area analyzed, using figure ground diagrams for the different cities (source: schwarzplan.eu). Thus, a typical average occupancy (not the actual) was applied. The ground area reference allows one to directly compare rainwater RO and greywater production.

2.3.3. Simulating Evapotranspiration of VGS

The potential evapotranspiration demand of VGS, denoted $ET_0{}^{\text{vert}}$ (L/m^2), was calculated based on verticalization of the well-established, adapted, Penman–Monteith approach, used by the FAO to calculate ET_0 [19]. $ET_0{}^{vert}$ simplifies the great variety of VGS described in Section 3 to virtually grass overgrown facades. However, the physically-based model approach describes the influence of site-specific meteorological parameters correctly. Meteorological input data (hourly values) originate from the Meteonorm 8 data base. Compared to the verticalization approach [20], the following simplifications were made: temperature, water vapor pressure deficit, and wind speed were not adapted. Solar radiation data were calculated for the 90° inclined surface for eastern, southern, western, and northern orientations [21], assuming non-shaded facades for comparability reasons. The ground heat flux (G), which gets the wall heat flux in the vertical case, was negligible on a daily basis, at least compared to net radiation (R_n) and for the vegetation period [22], though it might become relevant during the heating period. Hourly values were aggregated to daily and monthly evapotranspiration sums (L/m^2) for the four orientations (Figure 2). All calculations were performed using MS Excel. For the comparison of the different cities, and with water availability, the average for all expositions was used.

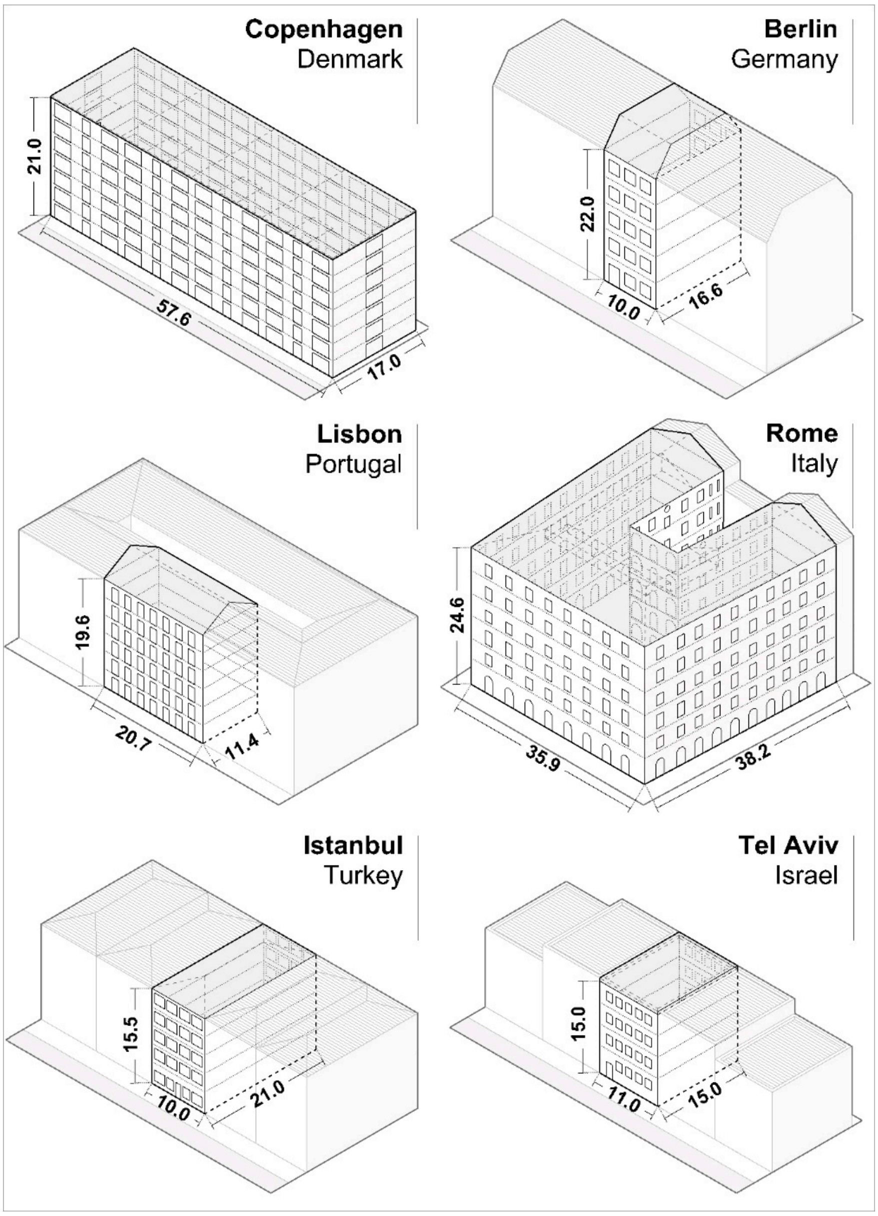


Figure 2. Selection of buildings representing typical architecture in quarters that are severely affected by urban heat islands (UHIs) in individual cities. The drawings are isometric. Illustration: Alessandro Stracqualursi.

2.3.4. Case Study Buildings from Copenhagen, Berlin, Lisbon, Rome, Istanbul, and Tel Aviv

Figure 2 presents the buildings identified as "typical" or "representative" in different cities, in quarters that are most affected by urban heat islands. The buildings, their architecture, uses, social structures, communities in the houses, as well as their lifestyles, are simplified in this study, and characterized with the following parameters: ratio of facade area to ground area (v/h), occupancy (O) as number of inhabitants per ground area, and greywater (GW) production rate per capita.

In Copenhagen, Denmark, the selected building is in the district of Vesterbro. Although heat stress is not expected to be a major problem in the near future, Vesterbro is among the districts where a UHI can be detected [23]. Stormwater management is of higher relevance for the city and has been focused on in the masterplan for Copenhagen, after the flood of 2011. The case building named "almene" represents the typical Danish social housing type built in the 1960s and 1970s. It accounts for around 20% of the building stock in Denmark. The "almene" buildings are typically linear, with six to seven stories, and contain many apartments [24,25].

The building from Berlin, Germany, was typical for the Wilhelmine period between 1880 and 1918. Dugord et al. [26] identified this building type stock as having the highest risk for heat stress in Berlin. These buildings represent approximately 10% of Berlin's residential building stock and are inhabited by 25% of Berlin's population. The Wilhelmine buildings typically have four to six floors with closed or partially open courtyards [27], and represent typical dense block developments [28].

The model building in Lisbon, Portugal, was selected from areas in the city with the highest population density and urban heat index [29]. The location is in the historical center of the city, the former districts of Madalena and São Nicolau, with a total area of 0.2 km^2 and 1875 inhabitants (2011 population Census, [30]). It represents a Pombalino style building, a design that followed in the reconstruction plan of the lower part of the city, called "Baixa Pombalina", after a major earthquake and tsunami in 1755. Pombalino buildings have four floors and a dormer. The building's floor area was calculated from the average of 651 buildings in "Baixa Pombalina", located in 81 homogeneous blocks. A typical window size and floor height were calculated by Miranda [31] and Morais [30], respectively.

The building in Rome, Italy, is located in the central Esquilino district. With a population density of 10,813 inh/km^2, it is one of the most densely populated districts in the city [32]. Esquilino suffers from severe urban heating effects [33]. The building (a traditional, rigorous residential type) was constructed in 1873; it has a linear geometry, commonly found in the Esquilino. Impervious terraces and clay tile sloping rooftops are present in almost all buildings in the historical center of Rome [34].

The typical building in Istanbul, Turkey, is situated in the central and historical district of Kadıköy. This is the most densely populated, urbanized area on the Anatolian side of Istanbul, affected by the UHI effect [35]. A typical building in Kadıköy has five to seven stories. Information on a typical building involves the average values from a building block of row houses, forming an open courtyard, from the General Directorate of Land Registry and Cadastre [36].

The model building in Tel Aviv, Israel, is situated in the Florentine quarter, which is one of the most susceptible to surface UHI effects. Early urban planning was shaped by the Geddes Plan from 1925, characterized by a hierarchical grid of streets that form blocks, central open spaces incorporated in blocks and dwellings, and a standard small-scale residential building type [37]. The selected building is located at the crossing of Herzl Street and Wolfson Street, in an area of compact mid-rise buildings, with 3–5 stories, and very few trees on the street. The population density in the area is 12,236 inh/km^2.

3. Results

3.1. The "Wicked Problem" of Water

The urban heat island (UHI) effect is a well-known characteristic of the urban climate [38,39]; it is amplified by ongoing urbanization and the sealing of surfaces, and can result in serious health hazards [40,41]. Heat-mitigation strategies implemented at the level of individual buildings, using VGS or GRs, are well known, and can be traced back to ancient times—in some cases providing privacy and food provision [42].

The current emphasis on NBS_u integrated in the building envelope is heavily attributed to reducing the energy consumption of the building itself, functioning as thermal insulation, wind protection, and passive shading. In addition, they can moderate the microclimate of the immediate surroundings, through the cooling effect from plant transpiration. This process highly depends on the available water supply [43,44]. The most common source for this is tap water from the existing water supply system—but with the ongoing transition to a CE and the implementation of NBS_u, it is clear that the predicted increase in fresh water withdrawal is not sustainable, and calls for a change in this practice.

The nature of water, as a resource, makes it inherently scarce, with unprecedented demands on water supply for both consumptive and non-consumptive use. These stresses are unequally distributed in time and space, and create an ever-changing landscape of consumption patterns due to industrialization and urban migration, while each sector is simultaneously seeking to maximize the stream of social and economic benefits from a limited resource [45]. A relatively under-represented source of water stress can be attributed to NBS_u for the mitigation of UHI effects. For example, NBS_u for stormwater management need artificial irrigation during the dry season, when plants contribute to cooling. Here, the "wicked problem" for urban water management is identified. On the one hand, more service provisions require higher water use, which is commonly solved by importing water from outside of the city. On the other hand, fresh water enters the city, becomes polluted, is discharged (whether treated or not), and leaves the city. One key to ensuring sustainable water supply for urban irrigation and cooling through plant transpiration is, thus, implementing water reuse.

At the building scale, one often-discussed approach is the local use of rainwater, especially for GRs. For VGS, some literature demonstrates the potential of rainwater use [46,47], but detailed experimental investigation is scarce [48]. Rainwater harvesting systems have proven to be effective as partial substitutes for domestic water demand in oceanic zones [49], as well as in semi-arid climatic zones [50], but limiting factors include the unpredictability of precipitation patterns and the size of water storage systems, which may be prohibitive [14]. On the other hand, wastewater, particularly greywater, is produced daily and, hence, can provide a continuous stream of irrigation water once treated.

3.1.1. Closing the Water Cycle at the Building Scale

In addition to rainwater harvesting, source separation and on-site treatment of wastewater is a key element for CE in the water sector. However, using these sources, changes must be made at the scale of the building and its service systems. In addition to these changes, there are important implications for the surrounding wastewater discharge infrastructures.

Firstly, the building needs sufficient collection facilities. Secondly, since irrigation requirements are time-shifted, relative to the actual precipitation or the production of greywater, the system must provide a buffer reservoir during dry periods and a distinct pipe system to collect and distribute the water. Lastly, if greywater is used, the system must locally treat the wastewater part of the stream. Additional installations for collection and storage are necessary for both the purification of greywater (e.g., in GRs) and the use of locally purified greywater for irrigation. Whereas the first needs pre-treatment (i.e., settling tanks or filter units), the latter needs biological treatment as well [51–53].

Either way, in existing buildings this is usually not possible without intervention in the building structure or envelope; moreover, it is correspondingly cost-intensive [54]. The system components require additional space, as services detract from the usable area. For a new building, however, the additional costs, efforts, and impacts are estimated to be very low [54,55]. For such installations, operating costs (e.g., monitoring, energy for pumping, and aeration of the biological stage), as well as the time and cost for services and part replacements must be considered.

3.1.2. Embodied Energy in the Provision of Water

In this paper, water is considered a limited resource—and using rainwater or reusing greywater in NBS_u is considered as "closing" the local water cycle. Therefore, the implications of the provision of water for irrigation in the framework of LCA or life-cycle costs (LCC) is most likely considered an operational cost [56]. Some LCAs integrate the water footprints of the materials that are implemented in the research [57], and in some cases, the energy use or heat production can be transformed into a water footprint [58]. However, the real costs and energy consumption required to obtain, treat, and provide tap water to the user are rarely included in the calculation.

Energy costs represent, on average, some 30–40% of the operational costs of water services [59]. In the case of water supply, this percentage can be as high as 80% [60], and as such, reducing the required fresh water supply by reusing greywater for non-potable uses has the potential to provide significant savings in energy consumption in water supply systems.

The embodied energy in the water supply represents the catchment and treatment, on the one hand, and the distribution (pumping), on the other hand [61]. The latter depends highly on the topography of the serviced area, and can triple the amount if located in a hilly region. The amount of energy for pumping can be calculated for a customary device and pipes, resulting in approximately 0.02 kW h/m^3 100 km without raising the altitude level. Lifting the water by 500 m in altitude doubles the energy consumption to approximately 0.04 kW h/m^3 100 km [62]. For the catchment and treatment of water, Table 2 provides specific embodied energy values from different sources.

Table 2. Embodied energy for water extraction, conveyance, and treatment (modified [63]).

Water Source	Primary Energy Drivers	Energy Consumption in kW h/m^3	
		Range	Average
Groundwater (distribution included)	Pumping	0.27–1.30	≈0.5
Surface Water	Pumping	0.5–4.0	
Brackish Water	Reverse osmosis	1.2–4.0	≈1.5
Seawater	Reverse osmosis	2.5–10.0	≈3.5

Table 3 presents embodied energy values for water in five different countries and cities. The values in Table 3 are often calculated as gross figures (input into the distribution system) by the provider. The losses within the network are not included. Therefore, the actual water withdrawal at the tap does not represent the actual energy footprint per inhabitant. For example, in Italy, the daily water demand of 220 L/inh d in the year 2015 was accompanied by water losses of 47%, equaling a net volume of 428 L/inh d [64].

Table 3. Specific embodied energy values for water in kW h/m^3. If citation is not provided, the value represents a summary of the given partial value from the literature.

	Catchment, Conveyance, and Treatment	Distribution	Combined Energy for Water Provision
Country	——kW h/m^3——		
Germany Brandenburg	0.43 [d]	0.11 [d]	0.5–0.7 [a] 0.54
Denmark Copenhagen			0.2 [a]–0.6; 0.43 [b] 0.3 [b]
Israel	3.0–3.5 [c]	0.4–1 [c]	3.4–4.5
Istanbul			1.73 [h]
Portugal		0.33 [f]	0.33–0.55 [g]
Italy	0.184–0.45 [e]	0.146–0.325 [e]	0.330–0.775 [e]

Note: [a] [65], [b] [66], [c] [67], [e] [68], [d] [69], [f] [70], [g] [71], [h] [72].

3.1.3. Technical Facilities for Greywater Treatment at the Building Scale

Irrigation of NBS_u with treated greywater reduces the amount of fresh water required, on the one hand, and on the other hand, closes the water cycle on-site for some portion of the wastewater [53]. The needed treatment of greywater can either be carried by the NBS_u itself [13] or by using established intensified onsite treatment systems, as listed in Table 4.

Results for irrigating seasonal plants with raw or treated greywater vary among species. However, it should be noted that using greywater for irrigation purposes could have positive effects on the growth of plant biomass when compared to nutrient-free tap water [73]. Furthermore, only a minor uptake of micropollutants (e.g., heavy metals) in the plants, and no presence of pathogens on the plant surface, were found [74].

Table 4. Feasible small-scale greywater treatment plants and their analogous specific energy consumptions from medium scale plants (adapted from [75]).

Feasible Small-Scale Treatment Technology for Greywater	Analogous Average Energy Consumption [kW h/m^3] (From Medium Scale Treatment Plants for Conventional Wastewater Treatment)
Biological stage	
SMBR	0.2–4
SBR	0–0.29
BR	0.66
Disinfection	
UV Disinfection	0.02–0.8
RO	0.56–1.3

SMBR: submerged membrane bio reactor; SBR: sequencing batch reactor; UV: ultraviolet RO: reverse osmosis.

In Table 4, a number of ready-to-use small-scale treatment plant technologies that fit the requirements are listed. The energy consumptions of medium-sized treatment plants are used here due to the lack of reliable comparative values.

The energy consumption figures presented in Table 4 are for decentralized treatment plants. Energy demand for smaller treatment facilities will consume more energy per cubic meter of water due to the lower energy efficiency of small-scale systems. The impact of other energy consuming activities that are indirectly related to the process are not included. The energy use of treatment trains that produce service water for non-potable purposes range between 0.48 and 2 kW h/m^3 [75].

3.1.4. Nature-Based Solutions for Greywater Treatment at the Building Scale

The multifunctionality of NBS_u, such as GRs and VGS, includes their capabilities of acting as greywater treatment units. Here, design recommendations and processes occurring in treatment wetlands (e.g., biological degradation of pollutants due to bacteria metabolism in the pore space of the substrate) are transferred to develop GRs and VGS for greywater treatment [13,76–78]. Advances in this research are not only made at the lab-scale—full-scale applications are also available [79–82]. Besides the sufficient treatment functions of specific GRs and VGS, the daily available greywater also acts as irrigation water, providing and underlining the multifunctional purposes of NBS_u [82]. As, here, water supply is not limited in the dry season, cooling by transpiration (and therefore UHI mitigation) is an important effect of NBS_u treating greywater. The treated greywater can further be reused for the irrigation of other NBS_u.

3.1.5. Policies and Regulations to Support Water Reuse

Policies and regulations reflect the regional, national, or international perspectives and priorities on agreed objectives. They provide a framework, defining rights and obligations of the affected stakeholders, and are shaped according to their needs. In particular, with the needed shift towards CE and closing loops in the water sector, policies and regulations need to be adapted to “not act” as barriers [15].

In 1973, the World Health Organization (WHO) published their first guidelines on safe use of wastewater, excreta, and greywater, with revisions in 1989 and 2006 [83]. According to the WHO, their use increased in both industrialized and developing countries due to higher water stress and scarcity, growing populations, environmental pollution, and a mind shift on wastewater, excreta, and greywater as resources [83]. However, the presented case study locations (see Section 2.3.4) do not face equal pressure on their water management systems. The Food and Agriculture Organization (FAO) [84] estimated freshwater withdrawal as a percentage of total renewable water resources, for the case study countries in 2017, as follows: Israel (67.3%), Turkey (28.4%), Italy (17.8%), Germany (15.9%), Denmark (12.4%), and Portugal (11.8%), reflecting the pressure on national water resources.

Among member states of the European Cooperation in Science and Technology (COST), several countries have obligatory standards or proposed guidelines on water reuse [13,85,86]. In Portugal, one recent regulation acknowledged water reuse as an alternative water source, in line with the principles of the CE [87]. Concerning the European Union (EU), water reuse is advised to be used “whenever appropriate” in the EU Urban Wastewater Treatment Council Directive [88], and addressed it as one of the possible supplementary measures to be optionally implemented in member state policies in the Water Framework Directive in 2000 [89]. Regulation 2020/741 [90] provides minimum requirements for treated wastewater reused for agricultural irrigation. Reuse for irrigation of NBS_u in cities is therefore not addressed.

The implementation of decentralized systems using non-conventional water resources is hindered by the lack of a regulatory framework, institutional support, and financing schemes for small and rural communities [91]. Regarding a regulatory scheme, regional policies can provide a basis for national or international policymaking. In Germany, there is no ordinance regulating rainwater management [92]. However, regional regulations, such as requirements for managing rainwater in the Berlin water act [93], might serve as a blueprint for national policy. Additionally, non-binding recommendations by professional associations are available in regard to handling rainwater and treating and using greywater [94,95].

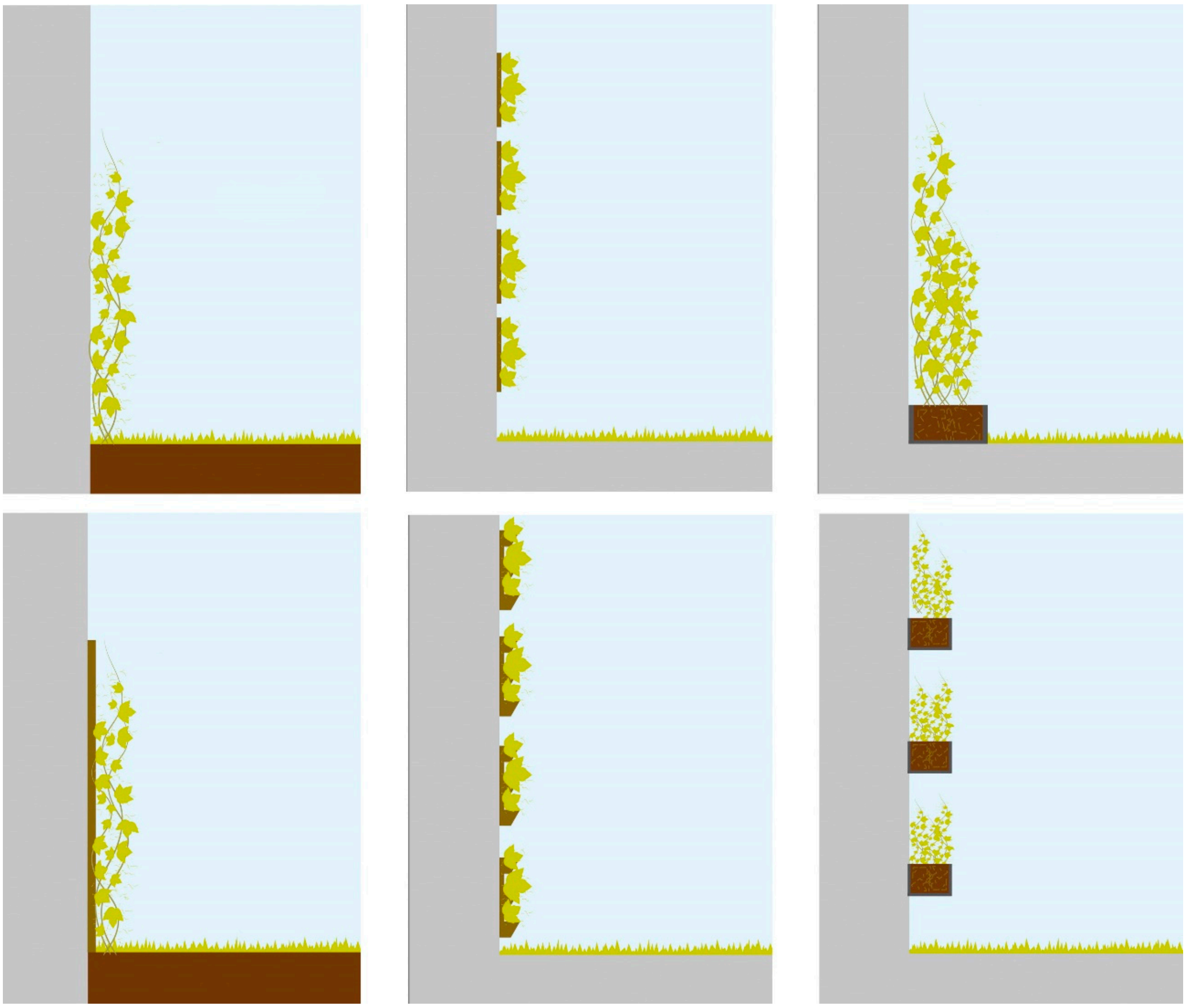
3.2. NBS Units Considered: Focus on “Building Greening” Systems

Within the framework of the COST Action “*Circular City*”, an extensive list of NBS_u was formulated to promote the transition to CEs in urban areas [7,9]. In this paper, *building-integrated* NBS_u, namely GRs and VGS, are discussed and analyzed for their constituent materials and water requirements. According to Pearlmutter et al. [10], green building systems comprise of the greening of building envelopes with living vegetation. In surveying the existing literature, we adopt the perspective of a LCA, in which material quantities are inventoried and assessed in terms of their environmental impacts. The following sub-categories of GRs and VGS are included in this survey, namely intensive and extensive GRs, as well as a ground-based green facade, a wall-based green facade, a pot-based green façade, and vegetated pergola.

3.2.1. Vertical Greening Systems (VGS)

Vertical greening refers to vegetated surfaces on the building envelope, which include the spread of plants that may or may not be attached to the façade, and can either be rooted into the ground or in pots (see Figure 3). Thus, based on the characteristics of the vegetation, support structures used, and root system, the type of green facades can be divided into a: soil/ground-based green facade, wall-based green facade, or pot-based green facade [7,96–98]. The typology of plants and associated thickness of the foliage, water needs, material characteristics, and layers, are relevant aspects when selecting these systems [56].

A ground-based green facade is a wall completely or partially covered with greenery (Figure 3a). The climber plants (evergreen or deciduous) are planted in the ground (soil, technical or recycling substrates) or in containers (filled with soil), and grow directly on the wall, or climb using climbing-aids (e.g., on a frame) that are connected to the wall [7]. These NBS_u can also be implemented along highly frequented roads to reduce noise emissions; they usually require less intensive maintenance and protection than pot-based green facades or wall-based green facades [7,56].



(**a**) (**b**) (**c**)

Figure 3. Types of vertical greening systems: (**a**) ground-based green facades, either self-climbing (top) or with support structure (bottom); (**b**) wall-based green facades, either with panels attached to the wall (top) or as stand-alone systems (bottom); and (**c**) pot-based green facades, with pots on the ground (top) or attached to the wall. Illustration: Dimitra Theochari (unauthorized use is not permitted).

A wall-based green facade comprises panels and technical structures (3D-frames filled with technical substrate) that are seeded or planted (Figure 3b). These panels and structures are fixed onto facades or walls or can be designed as stand-alone systems and allow the placement of plants and substrate on the entire surface. Some systems allow for the removal of panels during winter. Compared to soil/ground-based green facades, a wider plant range can be applied, though compared to the other types of VGS they require more maintenance due to the nutrients and watering system. Their durability varies depending on the chosen panel system [99].

A pot-based green facade involves the use of containers, such as pots or planters, which are placed on the ground in front of the building's facade or directly on the building or balconies [7] (Figure 3c). The containers of these NBS_u vertical greening types are filled with (technical) soilless substrates, soil, or a mixture, and some of them are also constructed like a GR with different functional layers (e.g., substrate, filter, and drainage layer). A broad variety of plant species (e.g., climbing plants, trees, shrubs, perennials) can be planted in the containers. Geared to the specific demands of plant species (e.g., climbing plants), supporting elements, such as cables, meshes, trellises, or nets have to be provided.

3.2.2. Green Roofs (GRs)

Modern GRs are engineered systems whose designs are informed by a broad knowledge base, supported in technical guidelines, standards, and scientific backgrounds. They comprise vegetation planted in a technical substrate, followed by several materials, arranged in layers, and installed on a constructed structure. They can be implemented at the ground level or on the top of buildings, respecting the physical integrity of the built structure.

In urban areas, GRs offer potential benefits in terms of aesthetic value, restoration of biodiversity, reduction of noise and air pollution, and mitigation of heat-island effects [40,100–103]. GRs are efficient solutions for stormwater attenuation, delaying the peak flow, and releasing water more gradually; thus, avoiding overloading the urban drainage system. The stormwater infiltrates and is retained in the GRs substrates, and is subsequently released during dry periods through evapotranspiration [100,102,104–106]. In both rural and urban areas, this solution can improve thermal comfort and yield economic advantages due to the reduction of heating and cooling requirements [40,100].

Two general types of GRs can be considered (Figure 4), based on the type of plants selected, the associated substrate depth, and the amount of maintenance expected [7]: (i) extensive GR; and (ii) intensive GR.

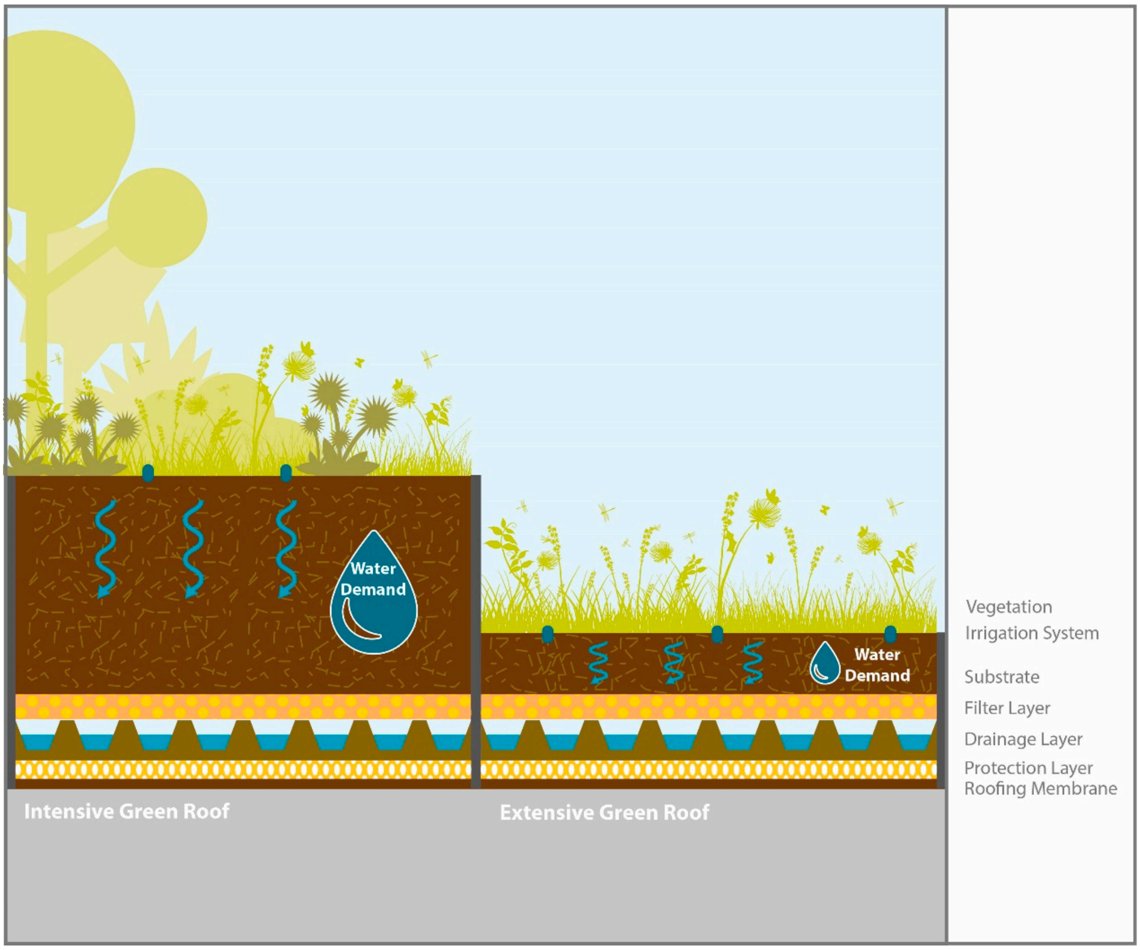


Figure 4. Green roofs of two general types: intensive (**left**), and extensive (**right**), showing typical layers common to both types. Illustration: Dimitra Theochari and Cristina Calheiros (unauthorized use is not permitted).

For the purpose of the present review, these two categories may be defined as follows.

(i) *Extensive green roofs*. The most common plants used are sedum, herbs, mosses, and grasses. The substrate is relatively thin (typically 0.1–0.15 m) and lightweight. They are usually not accessible to the public. The installation and maintenance are less expensive than that of intensive systems. Irrigation is kept to a minimum, depending on the climatic conditions [7,96–98,107]. To achieve this, vegetation is composed of self-sustaining and native species of plants that are chosen by taking into account their adaptations to local climate conditions [108].

(ii) *Intensive green roofs*. A wide variety of plants can be considered, from grasses to small shrubs and trees. Depending on the nature of the GR usages, the configuration, in terms of layers and substrate thickness (usually more than 0.2 m), may vary greatly. Intensive GRs are usually accessible for public recreation, gardening, relaxation, and socialization purposes [7]. Eventually, they can even become spaces for urban agriculture [40]. In general, this type provides more biotopes and higher biodiversity than an extensive system. On the other hand, higher costs for implementation and maintenance must be envisaged when compared to extensive systems, due to the increased loading on the structure [109]. In terms of maintenance, intensive GRs are similar to a garden, requiring regular irrigation and fertilization [10,110,111].

Either type of GR is typically composed of a number of consecutive layers, including the plants themselves, a growth substrate, an irrigation system, a filter layer, a drainage layer, a protection layer and roofing membranes, and an insulated structure, which is reliably waterproofed (Figure 4). Depending on the particular system, these layers may be built up in different sequences, or some even omitted, as in the case of "classical" GRs. These main layers have been described according to their typical functions and materials in recent publications [111,112].

3.2.3. Vegetated Pergolas

The history of vertical planting goes back to the hanging gardens of Babylon (c. 600 B.C.), considered one of the Seven Wonders of the World, and from ancient Egyptian gardens, we also find the origin of pergolas, which were further introduced in Italy. A pergola is typically a linear structure containing pillars and crossbeams, as well as an overhead latticework, commonly in combination with climbing plants to shade a walkway. Vegetated pergolas have traditionally been created with attention to the local climatic conditions, design purpose, and similar factors. In the 17th century, for example, different usages of ivy, climbing plants, roses, and grapes, were observed on the walls, hedges, or entries of castles, manors, and gardens, often using pergolas or similar support structures. Vertical planting design became easier by using steel cables to reach higher elevations and cover wider surfaces.

Design considerations for natural elements include physiological characteristics of trees or plants, their height, density of foliage, crown shape and volume, and whether they are deciduous or evergreen. In addition, maintenance considerations, such as growth rate, leaf, flower and fruit shedding, pruning, volume of root structure, and irrigation requirements should be considered, as well as environmental conditions, such as soil type, slope, and aspect, solar exposure requirements, and resistance to winds and pollution.

In some regions, particularly in Mediterranean climates, combining overhead vegetated pergolas with GRs are recognized as a way to create more enjoyable environments by mitigating urban heat [113]. While such traditional techniques of cooling and creating a more comfortable living environment are not new, they are attracting renewed interests in different parts of Europe, as it becomes clearer that greenery systems and plants provide a wide range of benefits to urban areas and their inhabitants. Ecologically-oriented architectural projects have been undertaken in historic areas in many European cities, demonstrating how the use of pergolas, as a mobile architectural form made of natural materials, can enrich urban landscapes [100]. In both Mediterranean and temperate regions, plants, such as vines and ivy, have been re-introduced to protect buildings against sunlight—just as they did in years past, when they were an integral part of the construction of vernacular architecture.

3.3. Materials for Green Roofs and Vertical Greening Systems: A LCA Approach

LCA studies on GRs evaluate the particular materials used for the various GR layers in terms of their environmental impact. The outcome of a LCA can be used as a decision factor in the design process and for comparison of the environmental performance of different GR types. The following phases are primarily included: material extraction, transportation, construction, operation, and end-of-life (EoL) [114]. Approximately 90% of the studies further discussed the inclusion of material and energy inputs for the operation and maintenance phase. This is crucial as, here, water is also respected.

Similarly, LCA studies exist, comparing various VGS in order to evaluate their environmental profiles [56,115,116], environmental benefits, and loads [117]. Cortes et al. [118] conducted a comparative LCA and, based on the findings, developed an eco-friendly module to build pot-based green facade systems. In order to achieve a sustainable profile, VGS need to include (in their designs) recycled materials and substrates, including natural alternatives with low environmental impacts.

3.3.1. Life-Cycle Inventory: Materials

Different types of GRs and VGS have wide ranges of material type requirements for their construction, operation, and maintenance. The choice of materials with minimized environmental implications plays a dominant role in their sustainable profile. Sustainable and local material choices are needed in order to have more environmentally friendly GRs and VGS [103,115,118–124].

Recent studies evaluated the replacement of conventional GR materials with natural alternatives [123] or with recycled material and industrial waste [122]. It was emphasized that GRs need to be developed using recycled materials as 'green' substitutions to conventional materials, and also the EoL phase requires further study because it is based on assumptions that are subject to great uncertainty given the nature of future applications at the end of the very long lifetime of GRs [114].

Table S1 (in Supplementary Material) presents the selected NBS_u and their typical constituent materials, broken down in basic types (organic, mineral, and synthetic), and highlighting their CE aspects (e.g., impacts and benefits). Tables S2 and S3 (in Supplementary Material) present lists of GRs and VGS materials whose inputs have been previously calculated, with information on their unit quantities and life cycle phases. These values are taken from previously published LCA studies, dealing respectively with GRs [57,103,119–121,125,126] and VGS [56,115–118,122,127].

3.3.2. Life-Cycle Inventory: Water

Freshwater withdrawal for a product may be generated by direct and indirect consumption. The water footprint (WF) concept expresses the amount, type of water resource, and pollution generated as a new metric that can be applied to a product, process, or service. It is expressed in terms of water volume per product unit (in terms of mass, energy, volume, etc.). The total WF is the sum of blue, green, and grey WFs, where the blue WF is the amount of freshwater (surface water and groundwater), the green WF is the amount of rainwater, and the grey WF is the amount of freshwater required to dilute pollutants in order to provide a level of water quality compatible with relevant water quality standards. This complex analysis of the water needed during the production cycle adds to the needed direct water use during operation and maintenance, mostly irrigation.

Most LCA studies only focus on the operation and maintenance phase, whereas the water footprint (including indirect water embodied in the materials of these systems) is not defined clearly. Table 5 presents a summary of the water consumption for irrigation, including the type of water used and the calculation method.

Table 5. Water consumption during operation and management phases included in a previous LCA and experimental studies on NBS_u): green roofs (GRs), and vertical greening systems (VGS).

NBS_u Type	Location	Plant Type	Calculation Method	Water Consumption		Reference
Extensive GR	Antananarivo, Madagascar	Grass	CML Baseline	96 L/m^2 a		[120]
	Calabria, Italy	Native Mediterranean plant species	precipitation + irrigation − run off	127 L/m^2 149 L/m^2	winter period summer period	[128]
	Lebanon	Sunflower	IMPACT 2002+	15 L/m^2	summer period	[56]
Intensive GR	Antananarivo, Madagascar	Grass	CML Baseline	730 L/m^2 a		[120]
	Puigverd de Lleida, Spain	Sedum, Lampranthus, Delosperma	EI 99	4032 L/m^2 a	June–August	[124]
Pot-based VGS	Delft, Netherlands	Pteropsida	Averaged for whole year	1 L/m^2 d	Planter boxes	[55]
				3 L/m^2 d	Felt layers	
	Madrid, Spain	*Hedera helix* stems biomass	ILCD Midpoint	8 L/m^2 d		[115]
	Madrid, Spain	Lonicera n. stems biomass	ILCD Midpoint	2 L/m^2 d		[115]
	Los Angeles, USA	*Liriope muscari*	-	6 L/m^2 d		[117]
	Portugal	*Sedum album*	CML 2001 Endpoint approach	8.7 L/m^2 d 340 L/m^2 a	Spring and summer Total	[122]
VGS	Hong Kong	*Peperomiaclaviformis*	CML-2001	100 L/m^2 month		[127]

3.3.3. LCA Studies: Sample Findings

A comparative LCA study [57] between traditional gravel ballasted roofs (TGBR) and extensive GR found that in both cases water consumption is mainly "embodied" in the reinforcing steel, concrete, thermal insulation, and waterproof membrane, while for GRs, the drainage layer is also a significant water "consumer". Several LCA studies have examined the individual components of GRs. For example, Vacek et al. [129] evaluated the environmental impacts of four semi-intensive GR (either a combination or something in between green roof types presented here), differing in their substrate composition. The system, including a substrate layer with an additional extruded polystyrene layer, has the highest environmental impact.

Cortes et al. [118] recently executed a comparative cradle-to-gate LCA of five existing modular pot-based green facade systems in order to determine the features that should guide the design process of a new insulation cork board (ICB)-based system. Results indicated that a medium density modular system could be an eco-friendlier counterpart to current plastic and metal based VGS, and the new ICB module supports the vegetation by offering better environmental performance. In addition, it can be easily recycled, it ensures the adequacy of both water retention and the drainage of excess water, and it provides thermal and acoustic benefits for buildings when used in external cladding systems.

Ottelé et al. [56] conducted a cradle-to-grave LCA, comparing several VGS to a conventional brick facade. The VGS investigated include two ground-based green facades, one with a stainless steel frame creating a cavity between the foliage and facade, one filled pot-based system, and one pot-based felt system. The irrigation systems are not considered when the climbing plants are rooted in the ground, as the water demand is covered by groundwater, and the other systems consume tap water (between 1 and 3 L/m^2 d as yearly mean).

The results indicate notable differences, especially for the supporting systems used for VGS. The materials for the frame structure based on stainless steel were found to have an environmental burden 10 times higher than for structures based on recycled plastic (HDPE), hard wood, and coated steel.

The felt-based system exhibited the highest values for global warming potential and fresh water aquatic ecotoxicity. This comes mainly from the waste generated by the need to replace the felt-based panels five times over the 50-year lifespan, rather than recycling the entire module with all of the material layers.

3.3.4. Building Greening Horizons: Areas for Improvement

In order to amplify the environmental benefits of GRs and VGS, and minimize their negative impacts, recycled or locally available materials play a crucial role—constituting an alternative to conventional materials by replacing them in key system layers. The so-called *zero waste strategy* represented by the six Rs (refuse, reduce, reuse, repair, recycle, and rot) is applicable to GRs and VGS, and is facilitated by organizations, such as *BauKarusell* [130], which acts as a social hub for urban mining, reusing, and recycling of construction materials. Essential information and know-how about CE, removal of buildings, re-used materials, and related concepts are provided by the *BauKarusell* [130] team for interested stakeholders in the building sector, including construction companies, building owners, architects, and landscape architects. For example, a specific case related to GRs is described by which the valuable extensive GR substrate from an existing building was carefully removed and reused in the GR construction of a new house.

Romm and Kasper [131] emphasize the potential of eco-efficient construction by using local resources available on building sites. During earthworks, carefully removed cohesive soil and nutrient-rich topsoil can act as a base for technical substrates, optimized with recycled materials, such as crushed brick and lightweight water-retaining materials (expanded clay or aerated concrete). This strategy allows the on-site reuse of valuable soil resources and the application of recycled building materials in the design process of new technical substrates, e.g., for GRs or pot-based green facades with high water storage capacity. Within selected Viennese building projects, such as *Wildgarten* (ARE Austrian Real Estate Development GmbH, 2019) and *Biotope City Wienerberg* (Forschungskonsortium Biotope City, 2021), this strategy (Concept Circular Soil) was implemented to save resources in building construction processes.

Eksi et al. [132] evaluated the potential of four recycled materials (crushed concrete, crushed bricks, sawdust, and municipal waste compost), and five locally available materials in Istanbul (lava rock, pumice, zeolite, perlite, and sheep manure), finding that the pumice and municipal waste compost mixture show good prospects in relation to the physical and chemical properties and positively influence plant growth, performing similarly to a commercial substrate, and better in terms of reduced carbon emissions. Other materials have been tested as alternatives to heat-expanded shale, such as crushed porcelain and foamed glass, and were shown to be good candidates for extensive GR applications [133]. Monteiro et al. [134] proposed an alternative experimental substrate composed of 70% expanded clay, 15% organic matter (granulated cork supplemented with urban solid waste compost), and 15% crushed egg shell, and found good results regarding plant establishment and water runoff, with a quality compatible with storage and reuse for non-potable purposes.

Reused materials for the drainage layer, such as PET bottles and bamboo, as well as substrate components, were observed to function well for GR [112]. Specifically concerning the drainage layer, ICB produced from processed cork waste has been evaluated as a material for water drainage and storage, replacing the polyolefin reference product, and replacing the conventional insulation layer made of extruded polystyrene (XPS) and expanded polystyrene (EPS) [135]. Rincon et al. [124] used recycled rubber from used tires instead of pozzolana gravel for the drainage layer in extensive GR, showing a high potential to reduce the heating and cooling loads in buildings compared to traditional materials. Additionally, the replacement of conventional pozzolana gravel (CPG) with recycled rubber crumbs (RRC) led to a significant reduction in acidification, eutrophication, and land occupation.

Within the GRs product descriptions of leading suppliers (www.optigruen.co.uk, accessed 10 July 2021), recycled materials can also be found: for example, 100% recycled synthetic fibers of polypropylene (PP), polyester (PES), and acryl are used for protection, and storage fleeces or drainage elements are made of 100% reclaimed and recycled HDPE. Due to their design (e.g., meander water retention board, FKM 60), these elements of GR are able to store high amounts of water. Hence, they have a high potential to contribute in a positive way to the urban water cycle.

Concerning VGS, Cortes et al. [136] evaluated the performance of expanded cork agglomerate as an eco-friendly alternative to conventional solutions made essentially of plastic and metal components. Results suggested that this solution offers the possibility of optimizing the retention and drainage properties of the system through the selection of the manufactured density to suit local weather conditions, thus achieving water retention of up to 20 kg/m^3 and providing rapid drainage of excess water. Furthermore, a better performance is expected in terms of thermal, acoustic, and environmental properties in comparison with conventional materials.

When considering recycled or alternative materials, however, it is important to ensure that they meet the guidelines established for GRs implementation in order to assure quality and security. Many of the reported studies have been carried out at a lab or pilot scale, such that further adjustments may be necessary for full scale implementation. A full LCA should be performed to substantiate the benefits of the alternative materials. Furthermore, when considering recycled and local products, availability should be taken into consideration to fulfill the demands of local industry.

These general considerations for improving the use of resources are becoming more important as it becomes ever clearer that the selection of suitable materials is crucial to reducing the energy and water use in different building stages and, in turn, the overall environmental impact of the building. Selecting raw materials from local sources, and those with low carbon emissions due to their potential to be recycled or reused, are thus part of a larger strategy of sustainability in the built environment.

Manso et al. [122] demonstrated how the integration of sustainability strategies (e.g., use of recycled materials, reduction of embodied energy, industrial waste reuse) into the design of GR and green walls can contribute to a lower environmental impact and therefore make them more competitive solutions. More specifically, this study evaluated the environmental impact of an innovative greening solution (Geogreen) in which the materials and processes of this system had a greater environmental burden and determined how these impacts can be minimized. It identified strategies for reducing by 74% the overall global warming potential (GWP) of the system, and minimizing the overall environmental burden compared to other construction systems.

In contrast to this broad approach, most studies have focused on particular components of building greening systems. Bianchini and Hewage [103] studied the production stage of different polymer applications (virgin and recycled) in the drainage layer of intensive and extensive GR and reported that recycled polymers were recognized as a beneficial alternative. This study determined that there were reduced amounts of nitrogen dioxide (NO_2), sulfur dioxide (SO_2), ozone (O_3), and fine particulate matter (PM_{10}).

Chenani et al. [119] analyzed the production and disposal stages of two extensive GR with comparisons in the (i) substrate layer (expanded clay and crushed brick with compost versus pumice and sand with compost); (ii) drainage layer (recycled polystyrene versus virgin polystyrene); and (iii) retention layer (recycled textile fibers versus Rockwool). Pumice and sand with compost, recycled polystyrene, and recycled textile fibers were recognized as environmentally beneficial alternatives according to the decreased abiotic depletion, acidification, eutrophication, and GWP impacts related to these layers. Vacek et al. [129] evaluated the three environmental impacts of abiotic depletion, acidification, and eutrophication in their study of the soil in the substrate layer and polystyrene in the water-retaining layer compared with artificial hydrophilic mineral wool in these two layers of a GR, and reported that, compared with soil and polystyrene, the use of artificial hydrophilic mineral wool was associated with an increase in environmental impact during the production stage and a decrease in the maintenance stage.

Pushkar [123] conducted an LCA on four types of extensive GRs, replacing natural perlite with the byproducts coal bottom ash and fly ash-based aggregates in both the substrate and drainage layers of GRs, finding that the result depended highly on the byproduct evaluation approach: with the mass allocation approach, this replacement was evaluated as harmful, with increased environmental impacts of approximately 5–20%, but with the system expansion approach, it was evaluated as beneficial, with decreased environmental impacts of approximately 20–40%.

Rincón et al. [124] conducted a comprehensive LCA in which the materials of two extensive GRs were compared with two conventional gravel ballasted flat roofs, with and without polyurethane as a thermal insulation layer, considering the production, construction, operational, and disposal phases—including experimental data on heating and cooling demands. Results showed the large contribution of energy consumption in the operational phase (over 85%) in comparison to the whole life-cycle impact for the existing roofing systems, and the authors concluded that recycled materials, in this case rubber crumbs from out-of-use tires, can be implemented in extensive GRs to improve both the insulation capacity and the environmental properties in Mediterranean continental climate conditions.

3.4. Simulation Case Study

3.4.1. ET_0^{vert} and Precipitation

The potential to evaporate water in the different case study cities depends on the climatic drivers and generally increases from north to south. Figure 5 shows the potential evapotranspiration ET_0^{vert} for the different locations differentiated by wall orientation and the provided precipitation over the typical year.

In Berlin and Copenhagen, precipitation is provided throughout the year and is in the same order of magnitude as the ET_0^{vert} during summer, while providing surplus water during winter. In the other cities, ET_0^{vert} is much higher than precipitation during summer for all wall orientations. In Tel Aviv and Lisbon, on average, no precipitation occurs in the summer for four and one month, respectively. In these two cases, but also in Rome and Istanbul, there is a highly negative climatic water balance in the summer months (Figure 5).

Regarding the different wall orientations, southern and eastern and western facades are most promising, in regard to evapotranspiration potential. Northern facades in the northern hemisphere have the lowest exposition to solar radiation and, thus, show the lowest ET_0^{vert}. Southern facades show the highest evapotranspiration potential during the winter months, while during the summer, eastern and western facades have the highest ET_0^{vert} among all orientations. The higher the elevation of the sun, the lower the amount of incoming solar radiation on the southern facade compared to east and west. This applies for the case study cities over a year, with the effect being more pronounced in the south than in the north.

ET_0^{vert} is the potential evapotranspiration, occurring when infinite water is available, considering climatic limitations. It should be noted that the real demand might be lower or higher due to the choice of plant species and maintenance status of selected plants. Furthermore, limitations for the overall greenable area might occur, such as window areas and legal restrictions in the construction e.g., for heritage buildings. Finally, in a realistic setting, radiation as the main driver is influenced by shading of neighboring obstacles. For further analyses, shading simulations can be included in established building simulation tools. In that case, 3D models of buildings are required.

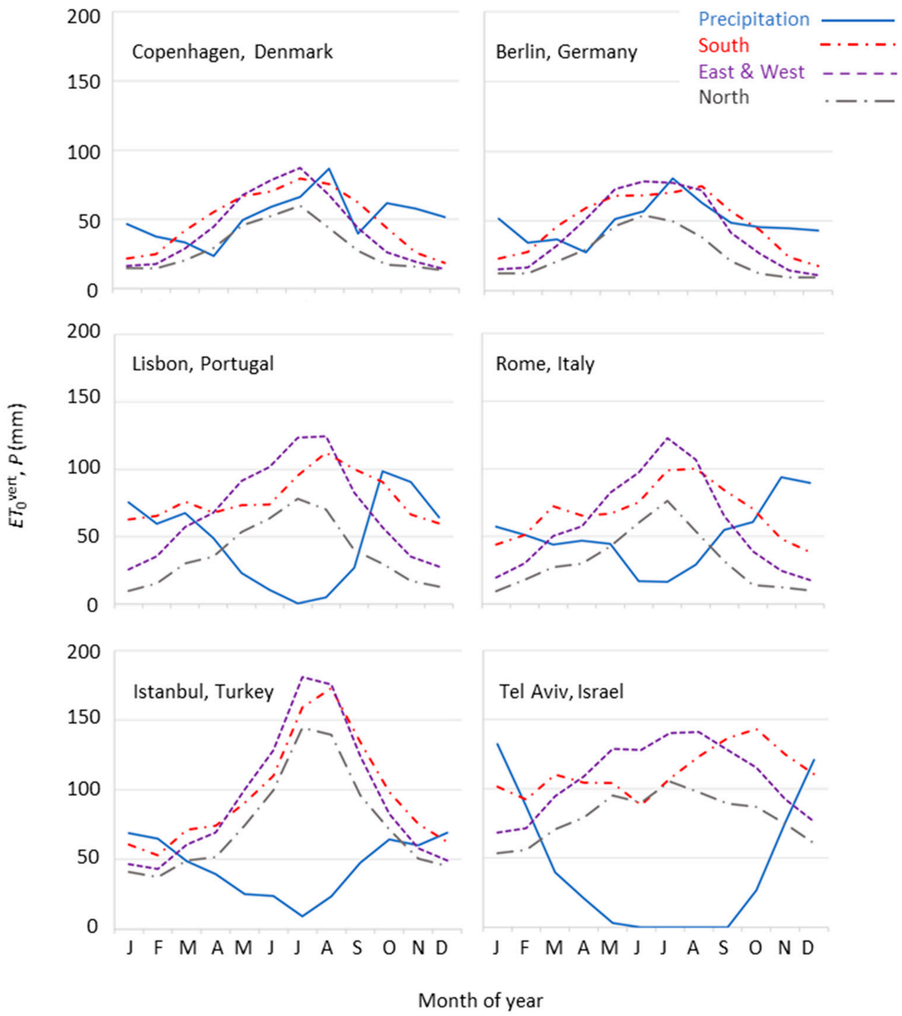


Figure 5. Long-time average standard evapotranspiration for vertical greening systems (VGS), $ET_0{}^{vert}$ (L/m^2 = mm) for the different expositions in the different cities together with precipitation P (mm) (Meteonorm, 2021; for the years 2005–2019).

3.4.2. Run-Off Reduction Potentials

While the climate determines $ET_0{}^{vert}$ and P, architecture determines RO from rainwater, its amount compared to the facade area and the amplitude of $ET_0{}^{vert}$. Thus, the different temporal dynamics of $ET_0{}^{vert}$ and P depicted in Figure 6 are changed substantially when comparing $ET_0{}^{vert}$ and RO. In short, the surplus of water in the winter is hardly detectable while the water shortage in the summer is clearly visible for all cities. The efficiency number e_{RO} intuitively describes how much of the run-off RO can be recirculated to the atmosphere by evapotranspiration of VGS (Figure 6). It is calculated by:

$$e_{RO} = ET_0^{vert} \frac{1}{P\,RC} \frac{v}{h} \tag{1}$$

in which v/h is the relation between the vertical facade area, v (m^2) and the horizontal ground area, h (m^2) of the case study buildings given in Table 1. The ratio v/h relates e_{RO} to architectural features (i) of the building itself as it determines ground area to facade area, thus collecting to potentially evaporating area; and (ii) its arrangement in the city, which influences the available facade area. The arrangement in the city also determines the orientations of the facades and shading of facade parts (not considered). The different morphologies are represented by the examples from Rome and Copenhagen—three and four facades visible vs. Berlin and Lisbon, with only two facades visible (Figure 2). RC

and thus *RO* depend on the roof typologies. Due to the flat vs. tilted roofs, *RO* of the case study buildings in Copenhagen and Tel Aviv is higher than that of the buildings in Istanbul and Lisbon, respectively. However, in this study, a constant *RC* of 0.9 has been applied for comparability reasons. Note, that the static *RC* concept used in this study has not been developed to analyze water availabilities, but for maximum runoff prediction, thus allowing possible overestimation. Otherwise, an improved rainfall run-off model, using single rainfall events would need to be applied [137].

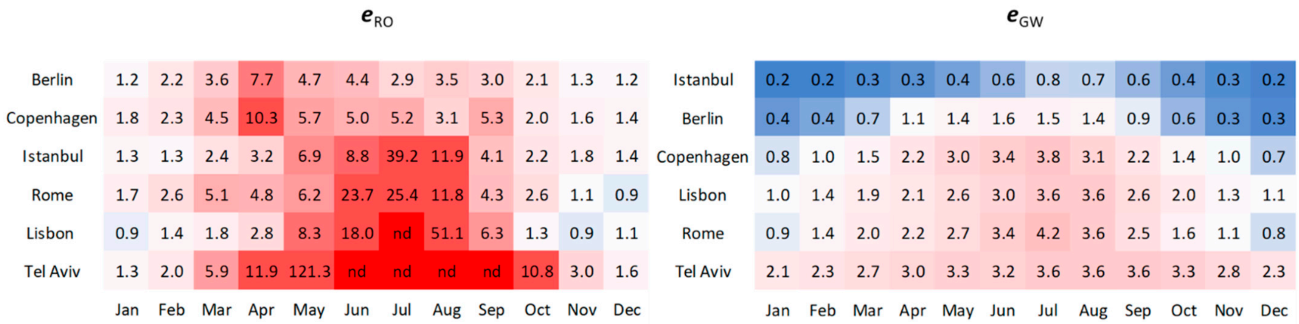


Figure 6. Monthly values of e_{RO} and e_{GW}, with e being the efficiency number describing how much of the accruing respective water can be evapotranspirated by VGS, calculated here as the ratio of monthly sums of $ET_0{}^{vert}$ and the respective water resource (**left**: available rainwater runoff from the roof *RO*, **right**: greywater accruing in the building *GW*) for the different cities (applying long-term averages for meteorological parameters 2005–2019; Meteonorm 8, Meteotest Bern, Switzerland). Note that the cities are ordered differently in the two figures.

Generally, $e_{RO} < 1$ indicates that only a part of the RO can be evaporated by the VGS—a surplus of RO—regarding a fully greened facade and sufficient water supply of the plants. In this case study, even with precipitation being higher than $ET_0{}^{vert}$ for all cities for at least two months, $e_{RO} < 1$ occurs only for one month in Rome and two months in Lisbon. That demonstrates the strong impact of the architecture, especially v/h for the buildings in this case study.

In contrast, $e_{RO} > 1$ indicates the potential of the VGS to evapotranspirate more water than available from the building's own roof—regarding a fully greened facade. In this case, the plants might be exposed to water stress. For most months in the case study cities, there is a virtual deficit regarding RO with the factor being at least 2.8 in the summer. That means, that a greened facade can evaporate the RO from 2–3 similar buildings—or that the greenable fraction of the facade is smaller than 1. Greening only parts of the facade would ensure sufficient irrigation of VGS. The reciprocal of e_{RO} gives the fraction of the facade area that could be greened using RO. Identifying the lowest of these values over the year gives the fraction of the facade, which can be sustainably irrigated (Table 6)—without considering the uncertainties regarding water availability caused by climate change.

Table 6. Water management potential for three different irrigation regimes: (**a**) solely run-off (RO) used; (**b**) RO irrigation prioritized, but drought months outbalanced with greywater (GW); (**c**) RO irrigation prioritized, but all months added with GW.

City	Water Management Potential							
	(a) Solely RO Irrigation		(b) Optimized RO Irrigation			(c) Full RO + GW Irrigation		
	Facade Greened	Evaporated RO	Facade Greened	Evaporated RO	Evaporated GW	Facade Greened	Evaporated RO	Evaporated GW
	%		%			%		
Copenhagen	10	35	26	79	11	46	92	41
Berlin	13	39	64	95	29	87	100	47
Rome	4	17	24	64	21	28	67	27
Lisbon	-	-	28	44	28	28	44	28
Istanbul	3	9	100	100	30	136	100	45
Tel-Aviv	-	-	28	60	53	28	60	53

In Istanbul, only 3% of the facade could be greened, which would be sufficient to evapotranspirate 9% of RO. In Rome, Copenhagen, and Berlin, 4%, 10%, and 13% of the facade can be greened, which would be sufficient to evaporate 17%, 35%, and 39% of RO. Thus, VGS can reduce the accruing RO and the sewer utilization substantially.

In Tel Aviv and Lisbon, it is not possible to sustainably evaporate RO using VGS due to no-rain in at least one month. The NBS_u intended to evaporate RO would die due to drought stress. In Tel Aviv and Istanbul, this dilemma can be solved by (i) decreasing the greened fraction of the facade and increasing the storage volume to export RO from one month to the other; or by (ii) adding water from other resources. Storage capacity is not in the scope of this article; here, we only assume that the water from one month can be stored to be used for irrigation in the same month. Regarding the use of other water resources for VGS irrigation, because of ethical scruples, scarcity, and the high embodied energy, irrigating with tap water should be the last option. Instead, greywater is a promising resource to be used. It will be discussed in the following.

3.4.3. Greywater Management Potentials

Equivalent to e_{RO}, e_{GW} describes how much of the accruing greywater GW can be recirculated to the atmosphere by evapotranspiration of VGS. It is calculated by:

$$e_{\mathrm{GW}} = ET_0^{\mathrm{vert}} \frac{1}{GW_i\, O\, m} \frac{v}{h} \tag{2}$$

in which GW_{i} is the individual greywater production rate per capita (L/inh d), O is the building occupancy per building ground area (inh/m^2), and m is the number of days per month Figure 6).

Note that this study focuses on residential buildings and e.g., buildings of mixed use or office buildings have different GW production patterns.

3.4.4. Optimized RO-Irrigation Scenario

Using GW for irrigation during the drought season or for additional irrigation during the year enables VGS in Lisbon and Tel Aviv in the first place and increases the fraction of the facade that can be greened in the other cities. Adding GW also increases the evapotranspiration of RO if it is used with priority (optimized RO-irrigation scenario in Table 6). Doing so in Istanbul, Rome, Berlin, and Copenhagen, the fraction of facade which can be greened increases by the factor of 33, 6, 5, and 2.6, respectively. Applying GW just to fill up RO deficits in Istanbul allows to green already 100% of the facade and to evapotranspirate 100% of RO, while 30% of the accruing GW are used (see Table 6). Both Berlin and Copenhagen have suffered from cloudbursts in the last 10 years. Additional GW application allows to green 64% and 26% of the facades of the model buildings in the two cities which would increase the fraction of evaporation of RO to 95% and 79%, respectively. In terms of rainwater management and pluvial flooding prevention, which is an interesting aspect for decentralized actions in growing and densifying cities.

Compared to RO, GW is available in larger quantities for the case study cities, with less fluctuation over the year, which is expected to be of increasing relevance, keeping in mind climate change and the predicted increase in droughts. However, GW also fluctuates over time. Peaks in GW production is apparent in the morning and evening hours and variations in GW quantity can be detected in between seasons [138]. Additionally, it can be expected that fluctuations occur because of vacation seasons, different cool showering and warming bathtub using frequencies in summer and winter and special GW production patterns in flats used for touristic short-term housing. Furthermore, the accruing amounts depend on the actual occupancy of the buildings. In this study we employed average values for occupancy representative for the whole district and average individual grey water production rates. Thus, the variation of GW over the week, the month, and the year is underestimated here.

3.4.5. Full Greywater and Run-Off Irrigation Scenario

When the full GW amount is used to irrigate VGS, the fraction of the facade which can be greened sustainably increases again (except for Lisbon and Tel Aviv) and is limited by the month with the lowest sum of RO and GW. For Rome, the increase is marginal, which is due to the limiting water availability. For the other cities, applying the full amount of GW makes sense in terms of GW management but also for further RO evaporation (Table 6). In Istanbul and Berlin, thus, the full amount of RO can be evaporated.

In Istanbul, due to the high amount of available GW, which is a result of the high occupancy, more than the facade area (136%) can be greened. For the Berlin case, the greened fraction of the facade could be increased to 87%. In Copenhagen, the greened area could almost be doubled to 46 % of the facade. Thereby, the evaporated water equals 92% of the run-off. In Rome, the greened area could slightly be increased to 28% when compared to an irrigation regime where GW is only applied in times of drought season. In the cases of Lisbon and Tel-Aviv, the fraction of greened facade could not be raised further above 28% in the third irrigation scenario. As both cities have months with no precipitation, the amount of applicable GW is the limiting factor in both the second and third irrigation scenarios.

4. Discussion

The presented results from the literature and the simulation study indicate existing gaps in knowledge as well as applied policies.

4.1. Simulation Case Study

The chosen case study examples show that, based on the climate, architecture, and occupancy, it is generally suitable to include VGS in run-off and greywater management. The climatic conditions, in particular solar radiation as the basic driver, shapes the overall water management potential in each city. However, the examples showed that the architecture can overrule the climatic conditions as it determines the greenable area and v/h strongly influences RO/ET. What has further been presented is that greywater use for irrigation is advisable. It therefore should not be hindered by high investment costs for its collection and diversion system. When greywater is added to the irrigation regime that has prioritized run-off, the RO management rate can be raised as greywater outbalances deficits that would otherwise lead to water stress in the applied plants. A surplus in RO and greywater can either be drained or treated on-site and then recirculated to be used in the building, e.g., for toilet flushing.

There are three factors that limit sustainable rainwater management: (i) shortage of rainwater during the year, which limits NBS_u; (ii) shortage of greywater compared to rainwater in the rainy season; and (iii) shortage of space to be greened compared to occupancy and greywater production. They should motivate planners to seek quarter-oriented (instead of single building-oriented) solutions. VGS implementation can serve as a systemic solution integrated into the quarter management, as one facade has high potential to evaporate water from neighboring buildings. Exporting space or water resources from one building to the other or to horizontal green areas, such as GRs, could be an option to optimize the system, e.g., regarding pluvial flooding, mixed sewer overflows, and eutrophication in the quarter and watershed, respectively. With the simple, ground area, vertical area, and occupancy-based description of the buildings, we delivered an effective upscaling approach for neighborhoods, quarters, and districts.

4.2. Structural Issues

Several issues could arise from implementing GRs and VGS in existing buildings, such as structural issues, deficient performance, and EoL-time disposal [102]. Most buildings have load restrictions, especially older buildings with roofs that were not intentionally constructed to accommodate NBS_u. Accordingly, it is important to keep the weight of the GR (especially the substrates) as low as possible in order to avoid damaging the structure and its usability. It is important to note that GRs do not have to cause leakage problems, instead, protect the roof and its water-proof membrane from damage [102,139,140]. We highlight that the knowledge required to avoid these structural problems already exists, and should be implemented. This can be done, for example, by considering the roof slope [141], which can go up to 30° for the installation of the lightweight extensive GR [142], while ensuring a minimum slope of 2% in order to drain the excessive rainwater [143].

4.3. Ecosystem (Dis)Services

Although the provision of ecosystem services by NBS_u is substantial, knowledge gaps are still found in the quantification of the more intangible benefits of GRs and VGS, namely the gains in quality of life and well-being, for which interviews can be used [142]. There is especially a lack of research on the quantitative and qualitative benefits of ecosystem services in under-developed countries [144], an area where further research should be focused on.

Compared to the provision of ecosystem services, research on ecosystem disservices (ecosystem outputs that diminish human well-being, caused by NBS_u) is relatively scarce [145–147]. Open questions include fire-resistance in VGS [148], the quality of runoff water from GR [149–151], and air quality effects [152–154].

In humid weather, the adoption of GRs has the perceived disservice of attracting mosquitoes, though this risk is less than in gardens with open water bodies [155]. GRs can attract birds to the city, and while this could theoretically increase the chances for disease transfer to humans, such a risk has not been reported thus far [156]. Possible approaches to these issues may arise from existing strategies that have been adopted in parks and natural reserves [157,158].

4.4. Future-Proof NBS Units

An effort to adapt NBS_u to current and local climate conditions is being done by adapting the vegetation and substrate of GRs [102] and VGS [142]. Still, knowledge gaps can be identified regarding the impacts of seasonal climate variations on thermal performance of GRs and the evaluation of substrate vulnerability to wind erosion and heavy storm events. More critically, the long-term functioning of such NBS_u is seldom addressed. One way to do so is to quantify how each unit responds to stress, induced by water deficit, heat waves, and extreme weather phenomena. The resistance and resilience to stress of NBS_u can be evaluated by their capacity to resist change and their capacity to return to their functioning after the stress has induced a change. It can be assumed that those sufficiently irrigated are more resistant to water stress than non-irrigated NBS_u. When water stress is intense or long enough, plant selection, based on water need, is important. When not irrigated (or not regularly irrigated), units, such as extensive GRs or ground based green facades, are more likely to recover (e.g., roots in the soil can keep the plant alive, while species in extensive GRs can more easily recover from seed). However, there is very little empirical evidence of this, which limits generalizations, mostly because climate change is an ongoing process and there has been a limited exposure of NBS_u to it. Most knowledge on this topic is derived from natural and semi-natural ecosystems [159], with some general patterns emerging that can be applied to urban NBS_u, namely that NBS_u are more affected by extreme phenomena than by average values (e.g., longer heat waves, rather than increased average temperatures) and that multiple stresses are often associated to cause a change (e.g., a vertical wall can resist a heat-wave or a prolonged drought separately but not when they co-occur). One option for future research is to look for solutions that currently work in drier climates. This should include investigations on how xerophytic species perform under a Mediterranean climate type, to forecast the future response in other regions under climate change [160]. Further research on the resistance and resilience of GRs and VGS under climate change can provide guidelines on how to future-proof the functioning of those NBS_u in cities.

4.5. Policy Framework

Government regulations or incentives for implementing NBS_u in urban areas are diverse and differ between countries and between cities in the same country, and depend on the type of building ownership (private vs. public), age of building, and building area, among others. This dispersion can limit the application of GRs and VGS, which greatly depend on policy regulation for both financial and technical support [102,116,142,161].

To provide support to those interested in implementation, web-based solutions that aggregate information are of importance (e.g., https://www.greenroofs.pt/en/policy-map, accessed on 7 October 2021). Nevertheless, countries and municipalities can be limited in developing and applying appropriate legal rules and incentives due to their poor governance, low socioeconomic status, and less developed local market, as well as lack of clear guidelines in relation to project approval [162]. Moreover, unclear structural capability in case of renovation, collective ownership, and co-financing might become a legal limitation in case of GRs or VGS installation. Depending on the technology level used, costs of installation of GRs or VGS might become burdensome. In that case, investments by private owners are difficult to achieve. Accordingly, each country should select the most appropriate incentive policies and define them depending on their national and local conditions [161].

One way to overcome policy limitations when implementing NBS_u can be to reinforce the integration of NBS_u in building designs, which is already contemplated in the energy performance of building directives, to help improve the energy efficiency of buildings and reduce heating or cooling consumption. This could further help to achieve the circularity and decarbonized objectives, from a building perspective, by 2050. Technical solutions to integrate greywater and rainwater in the water management on a building scale are available and support a sustainable operation of GRs and VGS. Greywater and rainwater therefore need to be recognized and addressed in policies, as locally available resources, and distinguished from other often higher loaded streams of wastewater. In order to reduce pressure on freshwater systems, centralized energy, space-intensive water purification, and transport infrastructure, implementation of decentralized systems should be encouraged.

In order to enable circular urban processes in the built environment through NBS_u and by closing the local water cycles, moving forward to a more comprehensive evaluation of the climate change impact of buildings during their design, construction, and use will be key to performance in a carbon-neutral European (and worldwide) society and economy in the years leading up to 2050.

While the policy dimension to increase the use of NBS_u could benefit from further integration with ecosystem services [161], another future aim is to focus on the sustainable energy performance of buildings directive of the EU, which should be updated and contemplated in the new framework assessment and EU guidelines (various levels) as a method to enhance the circularity-related performance of buildings.

5. Conclusions

Water issues were dealt with extensively in this manuscript; moreover, water is identified as one of the major limitations in the implementation of the selected NBS_u. This leads to the introduction of the "wicked water problem", which needs to be addressed by a shift in the water use paradigm. The total water footprint of a system is comprised of the virtual water embodied in each individual component during its production cycle, and the irrigation water demand. The total sum needs to be respected when discussing the need for water reuse practices, as the virtual water needed is often neglected in LCA studies of GRs and VGS.

In fact, water could represent a common ground to measure most of the issues found. More specifically, we propose that water consumption, measured in terms of its equivalent energy consumption (or carbon emissions, to account for energy sources across countries), can be accounted in the entire life-cycle of the NBS_u, and included in its LCA.

Our case study demonstrates that the net water consumption of an NBS_u can be a powerful indicator of its "circular" performance, and in turn, its ability to contribute to the wicked problem of urban water. In particular, we offer the following conclusions, which advance the current state of knowledge in this realm:

- Based on the results obtained from a broad cross-section of cities in Europe, a vertical greening system could be a realistic option to manage on-site greywater and utilize rainwater captured on the roof of a typical residential building.
- The effectiveness of VGS for these purposes can only be understood based on the particular climate conditions of the urban site, most notably as a function of solar exposure that heavily impacts the water loss due to evapotranspiration.
- The potential of VGS must be evaluated with respect to the architectural design of a building, which can limit the vertical area that can absorb and evaporate water, as well as the horizontal area available for rainwater capture.
- The use of greywater for irrigation was shown to have clear benefits, as it can fill in deficits in available rainwater runoff, which would otherwise induce stress in the plants and potentially make VGS untenable. Therefore, policies should encourage and incentivize the on-site collection and distribution of greywater.
- The sustainability of water management, using circular systems, depends on the scale, and our findings reveal limitations in implementation within the scope of a single building, due to the available quantities of both runoff and greywater, and the relative area of VGS. Therefore, it is essential to consider this type of nature-based solution at the larger urban scale of a residential quarter, for instance, where mutual benefits can be made by sharing space or water from one building to other buildings, as well as outdoor green spaces in the vicinity.
- Considering the different possibilities of implementation, our case study results represent new approaches to more integrative urban settings, when compared to traditional building-based solutions.

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Article

Management of urban waters with Nature-Based Solutions in circular cities - exemplified through seven urban circularity challenges

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Abstract: Nature-Based Solutions (NBS) have been proven to effectively mitigate and solve resource depletion and climate-related challenges in urban areas. The COST Action CA17133 entitled "Implementing nature-based solutions (NBS) for building a resourceful circular city" has established seven urban circularity challenges (UCC) that can be addressed effectively with NBS. This paper presents the outcomes of five international elucidation workshops (with more than 20 European experts from different backgrounds) examining the effectiveness of NBS to address UCC and foster NBS implementation towards circular urban water management. The outcomes of the workshops identified 'Restoring and maintaining the water cycle' (UCC1) and 'Water and waste treatment, recovery, and reuse' (UCC2) as the two most relevant challenges for water resources in urban areas. Moreover, significant synergies with 'Nutrient recovery and reuse' (UCC3), 'Material recovery and reuse' (UCC4), 'Food and biomass production' (UCC5), 'Energy efficiency and recovery' (UCC6), and 'Building system recovery' (UCC7) were identified. Additionally, the paper presents real-life case studies to demonstrate how different NBS and supporting units can indeed contribute to the UCC. Finally, a case-based semi-quantitative assessment of the presented NBS was performed. The paper concludes by identifying the most typically employed NBS that enable processes for UCC1 and UCC2. This study presents a new paradigm and aims to enhance awareness on NBS's ability to solve multiple urban circularity issues.

Keywords: nature-based solutions; circular cities; sustainable water management; urban circularity challenges; water reuse;

1. Introduction

Water is a natural and essential resource for human life [1]. Water consumption has doubled in the last century as a result of global population increase, making water scarcity one of the most pressing issues of the twenty-first century [2-4]. Rapid industrialisation and economic growth [5], as well as the generation of substantial amounts of industrial effluents, place a significant strain on limited water resources [6-7]. Climate change is expected to have a significant impact on the water cycle [8-9], resulting in issues in cities such as droughts, floods, water resource pollution, and heat waves [10-11]. Meanwhile, water in urban ecosystems, including wastewater, drinking water, stormwater, groundwater, surface waters, and a variety of urban ecosystems in which water plays a vital role, is currently not treated in a cyclical manner. For example, the regeneration and reuse of wastewater is now a priority only for nations with considerable hydric stress or water shortages (e.g., China, Mexico, the United States, and Israel), yet this regeneration can occur without extra water treatment in some instances [12].

According to the European Commission, more than 40,000 million m^3 of wastewater are treated in the EU every year, but only 964 million m^3 of this is reused, revealing the potential to increase the volume of reused water by a factor of 6. In the transition towards Circular Economy (CE), wastewater management and sanitation are central to water circularity and sustainability due to the integration of nutrients and materials recovery, clean water production and energy production [13].

A circular wastewater management would integrate effluent reuse to close the loop between water supply and sanitation. However, a circular water system cannot be limited to merely connecting the outlet of present wastewater treatment plants to the inlet of water supply systems. Especially for cities where stormwater management, flood prevention, climate mitigation or greening of the cities is a more pressing issue than the water scarcity. It demands a shift towards system thinking, as all urban water issues are intertwined and cannot be sustainably solved by the traditional, siloed water management approaches [14]. The connections between processes can be diverse and the segregation of streams should be optimised in a case-to-case assessment based on local conditions and needs. Ideally, transport and contamination should be minimised, while energy-efficiency and recovery of raw materials maximised [13]. Thus, concepts such as treated effluent reuse in irrigation of commercial crops [15], local use of rainwater and greywater for toilet flushing, car-washing and garden irrigation [1,16] or separation of urine and faeces from greywater to maximise nutrients recovery [13,16] are gradually coming to the forefront of the discussion for a circular transition in the water sector. Cities all over the world must rethink and reinvent themselves as water smart cities, shifting from drained to sponge cities, using reclaimed water and only draining surplus water as a last choice, while still generating chances to green the city and improve liveability [10]. More and more cities thereby consider nature-based solutions (NBS) an integral part of their water management plans. The European Commission defines NBS as: "*Solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions*." NBS addresses societal challenges and enables resource recovery, climate mitigation and adaptation challenges, human well-being, ecosystem restoration and/or improved biodiversity status, within the urban ecosystems [17]. NBS can also effectively mitigate the urban flooding caused by high rainfall events [18-19].

The COST (*The European Cooperation in Science and Technology*) Action (CA) 17133 is "*implementing nature-based solutions for creating a resourceful circular city*" [36], emerged as a bottom-up initiative to study and research on NBS and their circularity. The main purpose was to test the hypothesis "*A circular flow system that implements NBS to manage urban biosphere nutrients and resources, will lead to a resilient, sustainable and healthy urban environment"*. The CA17133 is structured in five working groups and one has been dedicated to NBS and sustainable urban water utilisation (working group 2), which carried out the work herein presented.

Within the CA17133 seven urban circularity challenges (UCC) were selected [20]: UCC1) Restoring and maintaining the water cycle; UCC2) Water & wastewater treatment, recovery and reuse; UCC3) Nutrient recovery and reuse; UCC4) Material recovery and reuse; UCC5) Food and biomass production; UCC6) Energy efficiency and recovery; and UCC7) Building system recovery. These seven UCC provide a novel framework to discuss and plan a transition to circular e cities. From the perspective of the UCC, our working group dedicated to urban water identified the following key research questions:

1. From an urban water management perspective, what are the main urban circularity challenges?
2. What are (water) interconnections between the different UCC and how can these UCC be addressed by the NBS?
3. What can be learned from current NBS implementations?
4. How can NBS address or contribute to the UCC1 and UCC2?

Looking at what is currently available in the literature containing both NBS and water management as keywords, only a few works directly address the topic. Nika et al. [1] reviewed assessment methodologies, tools and indicators with a focus on the societal challenges. Snep et al [10] reviewed the different technological levels at which city trees and vegetated rooftops have been implemented. Mousavi et al [21] conducted a survey with Australian water professionals focused on the definition of NBS. Ghafourian et al [22] provided an analysis of recent literature about the economic impact of linear to circular transition in water systems. All contribute to the topic, but none reflect on any of the research questions herein formulated.

Hence, the working group aimed to critically contribute to addressing (identified or selected) research questions through a series of nine workshops with the participation of more than 25 experts from different disciplines and 22 European countries. This paper presents and discusses the major outcomes of the workshops aimed at fostering NBS implementation. It includes a water-centric conceptualization of the seven UCC, validated with a case-based assessment. Representative NBS units are detailed and discussed linking their functionality with the corresponding challenges they address. The list provides a solid base for a development of a novel case-based semi-quantitative assessment, which enables ranking of all the NBS and supporting units, for both circularity challenge UCC1 and 2.

2. Materials and Methods

The extensive methodology behind this paper, from UCC and NBS selection and definition, to NBS circularity characterisation, is fully described by Langergraber et al.

[20]. The aim of the methodology is to categorize NBS based on circular economy principles, which are: 1) regenerate natural capital, 2) keep resources in use, and 3) design out waste externalities. The work (Figure 1) is based on a series of five elucidation workshops (adapted from IDEA protocol [23]) conducted between June and December 2020 to 1) refine the list of NBS, according to their ability to fulfill circular economy principles, 2) evaluate the NBS according to their ability to address the UCC; and 3) categorise them based on evaluation [20].

The work herein presented is a further expansion of these participative methods which is summarized below.

First, a visual representation of the UCC interconnections was developed based on the experiences of these experts researching and working in water-related fields (section 3.1). Following, examples (section 3.2.1) that demonstrate the aforesaid relation were selected based on the expertise and knowledge available in the workgroup (see Table A1). Selected NBS were categorised (section 3.2.2), by defining a semi-quantitative framework using a three-level scoring system (Table 1). This assessment identifies the overall potential of the NBS units to address or contribute to UCC1 (restoring and maintaining the water cycle) and/or UCC2 (water and wastewater treatment, recovery and reuse). The framework for this ranking was defined to determine the “UCC mark”and a “Total Circularity Score” achieved by each NBS unit or supporting unit:

1. The “UCC mark” (ranging between 1 and 3) equals the highest mark awarded to the NBS among one of the enabling processes within each UCC;
2. The enabling process "treatment" within UCC1 equals the highest mark awarded to the NBS among one of the enabling treatment processes within UCC (excluding the ‘reuse of water’ enabling process);
3. The “Total Circularity Score” achieved by an NBS was calculated as the sum of all awarded individual marks for both UCC1 and UCC2, but excluding the enabling process "treatment" within UCC1, to avoid double-counting.

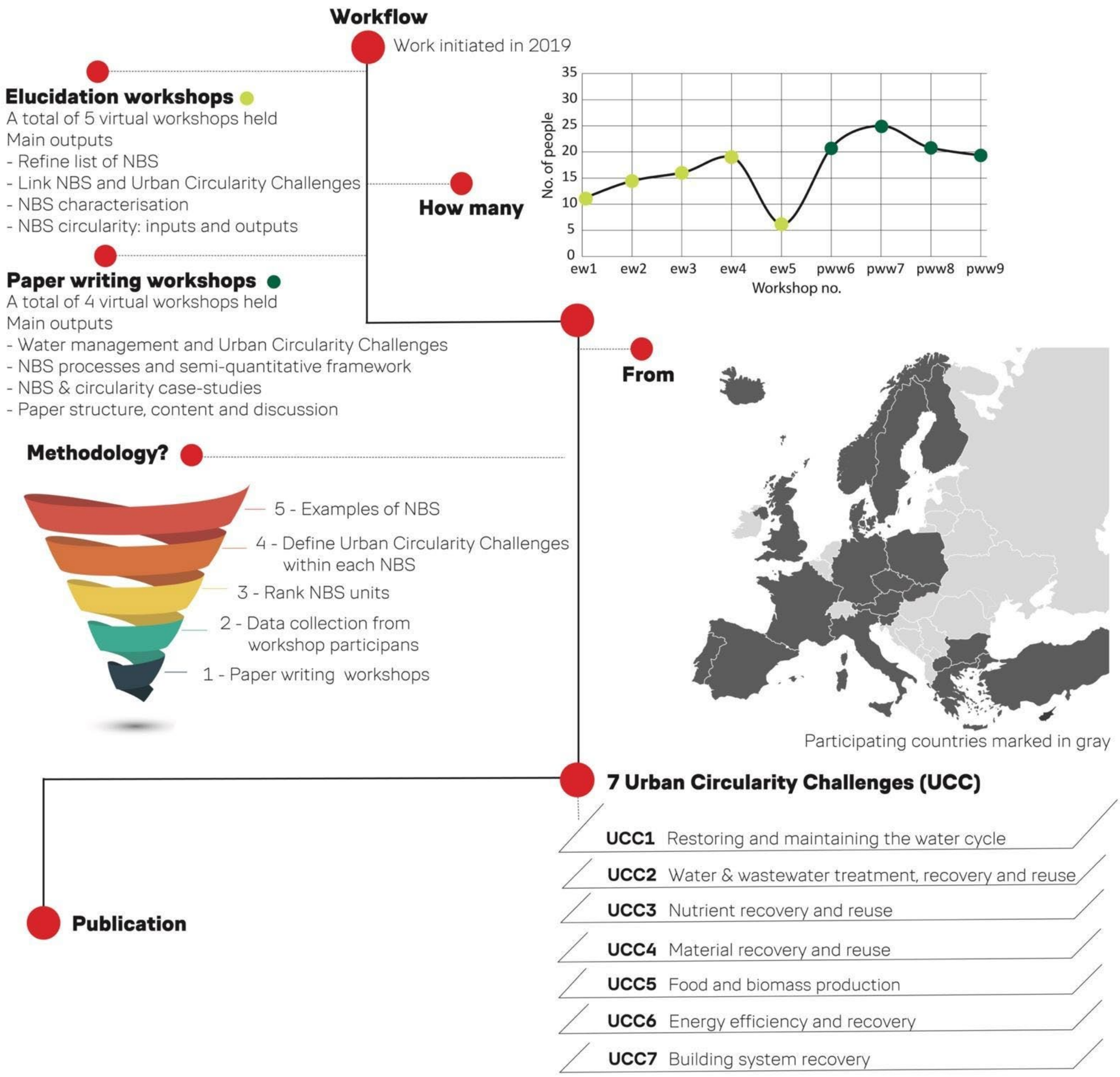

Figure 1. Schematic representation of the processes and workflow, including the details from the elucidation and paper writing workshops.

Table 1: Marking system used for the evaluation of NBS units and supporting units with respect to UCC1 and 2.

Mark symbol	Numerical mark	Mark description
●	3	Addressing the circularity challenge
●	2	Contributing to the circularity challenge
○	1	Potential contributing, depending on specific design

3. Results and Discussion

3.1. Urban circularity challenges

Langergraber et al. [20] have outlined a set of seven urban circularity challenges (UCC) directly addressed through NBS implementation in cities. Each UCC is central to achieving circularity, and should be viewed as interdependent objectives in a broader system context. There is an abundant and constant interaction between resources, energy and the needs of the urban population, and shedding light on the dynamics at different scales is fundamental to identifying the underlying causes of crises and appropriate points of intervention.

This section examines the interconnections between the UCC with a focus on water systems. Out of the seven UCC, two central challenges relating directly to water in the urban context are addressed in greater detail: UCC1) restoring and maintaining the natural water cycle, and UCC2) water and waste treatment, recovery and reuse. Starting from these two central challenges to urban water management, the interconnections with the remaining challenges are analysed and outlined. This includes practical experiences in linking various domains like urban agriculture, energy production, infrastructure and resource recovery.

3.1.1. Urban circularity challenges (UCC) with a focus on urban water

Figure 2 shows the seven UCC identified as critical issues in achieving circularity in cities, which can be addressed through various NBS. The diagram depicts the links between the challenges, categorised as either directly or indirectly relating to the topic of water. Blue arrows indicate a direct link to urban water, while grey arrows signify connections in a broader context, like contributions to climate change mitigation, reducing dependency on natural resources, and/or the reduction of our reliance on fossil fuels. The gradient arrow (blue-grey) connects UCC1 to the outer circle, which stands for contributions to climate regulation and possible mitigation effects in weather extremes, urban heat island effect, air pollution and climate change. Bi-directional arrows indicate an exchange or a flow path in both directions, while the simple one-directional arrows represent a one-way path from one element (challenge) to another. There are likely to be bi-directional flows between each of the system elements, but for the sake of simplicity, only the primary path directions are depicted in this diagram.

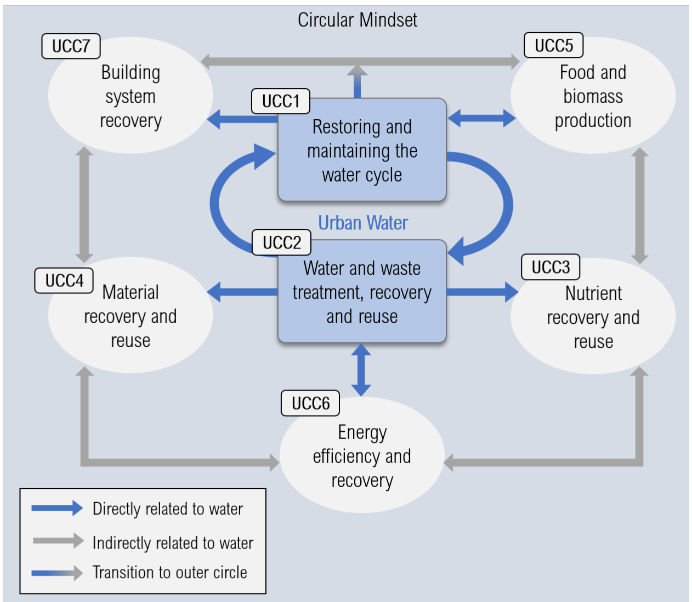

Figure 2. Diagram illustrating the interconnections between the seven circularity challenges from the perspective of urban water. The two central challenges of our analysis are (UCC1) restoring and maintaining the water cycle, and (UCC2) water and waste treatment, recovery and reuse.

Some of the connections between the UCC are obvious and already common practice, like rainwater harvesting for watering purposes and nutrient recovery from wastewater to be used as fertiliser [24]. Other connections are less evident and not yet well established, like recovering material from wastewater for use in construction [25-26].

3.1.2. Restoring and maintaining the water cycle (UCC1)

This challenge is related to the goal of restoring the natural water balance as far as possible. Built-up, urban environments are characterised by a drastically altered water balance, compared to that of undeveloped, natural landscapes. Sealed-off and hydraulically smooth surfaces combined with little to no vegetation result in higher runoff volumes and peaks, along with significantly lower proportions of infiltration and evaporation [27]. Climate change is expected to exacerbate this disturbed water balance. NBS are ranked as interventions with high manageability and high impact in terms of reducing flood risk in urban areas [11]. In this same category are measures to increase permeability [28]. By implementing NBS throughout the city, it is possible to begin re-establishing a more natural water balance, reducing runoff peaks and volumes and promoting infiltration, retention and evapotranspiration [29]. Groundwater recharge is an important factor in securing the drinking water supply of many cities [30]. Urban greening interventions can contribute to groundwater recharge by facilitating infiltration processes [31] and land restoration can increase the water holding capacity of natural land upstream of urban areas [32]. Increased evapotranspiration and mitigation of the urban heat island effect can be achieved by the planting of trees and other vegetation along roadsides, in rain gardens, meadows, green roofs and green facades [33-37]. A majority of the studies have shown the beneficial effects of green roofs in delaying the peak flow rate and reducing the total runoff volume discharged into combined sewer systems [38-40]. A wide array of NBS can contribute to restoring the natural water balance, including various infiltration and retention options. For a more detailed list, the reader is referred to section 3.2.

3.1.3. Water and waste treatment, recovery and reuse (UCC2)

The challenge 2 addresses the matter of recovering rainwater and reusing wastewater to reduce the consumption of clean drinking water, while relieving urban drainage infrastructure and treatment facilities and protecting downstream freshwaters from the pollutants contained in runoff water, blackwater and greywater.

NBS has changed the approach of dealing with urban water [41]. The concept of circularity dictates focussing not only on waste valorisation (i.e., through treated wastewater reuse), but also on the treatment process itself, by using eco-designs such as the various NBS systems [29]. NBS as urban green infrastructure provides sustainable solutions to the pressing issue of water management in urban and peri-urban areas. For example, the rise of the constructed wetland technology shows that wastewater management is viewed from a different angle; the goal is no longer one-dimensional (wastewater treatment), but extends to the provision of multiple benefits such as ecosystem services, habitat creation sites, urban wildlife refuges, recreation and landscaping [27,42-43].

Rainwater, in particular, is a valuable resource for local uses like gardening, washing cars and laundry. Rainwater harvesting can reduce reliance on groundwater and other freshwater sources, for uses that do not demand the high-quality standards of drinking water. Utilising local water resources can increase urban resilience in regards to UCC1, complementing and relieving large scale water supply systems that are susceptible to failure. Intercepting and harvesting the water from precipitation before it forms runoff in the urban catchment not only presents an additional, low-cost water source, but also contributes to re-establishing the pre-development water cycle [44-45].

In the context of UCC2, the central idea is to adopt a 'fit-for-purpose' approach in water use. Instead of treating all used water streams equally, conveying them in combined sewers and putting undue pressure on the treatment facilities, a circular water system is conceived to differentiate between varying sources and qualities of water. Recycling household greywater for laundry and other washing purposes, along with rainwater harvesting, are common examples of this approach. A significant barrier to operationalising this on a city-wide scale is the requirement for adapted piping in buildings. Retrofitting large parts of the existing infrastructure would be an expensive and logistically challenging undertaking, although it can be considered a good opportunity for replacing ageing infrastructure for implementing circular systems. Public perception in regards to domestic water reuse may present a more significant barrier [46-47].

3.1.4. Nutrient recovery and reuse (UCC3)

The UCC3 addresses the need for nutrient recovery and reuse. In the context of urban water, this relates specifically to the nutrients present in used water streams, and the different systems for recovering these nutrients. Fertiliser production is a prominent example of recovering nutrients from used water streams. This has the added benefit of preventing eutrophication in downstream freshwaters [48].

Non-grid, small-grid and hybrid urban wastewater systems permit source separation and optimisation of water management and use. Blackwater from toilets and greywater from sinks, showers and washing machines can be collected separately for onsite treatment or for non-potable water uses. Reuse options for greywater include toilet flushing, infiltration for aquifer recharge or irrigation. Sludge can be collected for centralised treatment. Urine diverting dry toilets are another option for collecting urine for onsite treatment and conversion into fertilizer, for use in urban agriculture. Similarly, brown water and greywater can be collected in a single stream for centralised treatment [49].

There is a strong link between UCC3 and the two central water challenges, UCC1 and 2. The potential for reclaiming nitrogen and phosphorus from household wastewater through a range of different processes, like source separation or fertiliser production from sewage sludge, is well established, and should be further promoted [50].

3.1.5. Material recovery and reuse (UCC4)

Urban circularity challenge 4 concerns the materials pathways, and the possibilities for recovery and reuse within the urban environment. The main link identified to the central water challenges is the connection from UCC 2 to 4. Wastewater has gained attention in recent years, as a source not only of nutrients, but also raw material for various other products.

Wastewater sludge and incineration ashes have been used successfully in the production of construction material, consisting either in part or whole of recovered material. Alayish and Çelik [51] report the use of dewatered sludge from a local water treatment facility to produce a viable, artificial lightweight building aggregate. This recovered material presents an alternative to conventional cement, and solves the issue of surplus sludge disposal [51]. Bioplastics, paper and cellulose are other examples of products that can be produced from used water sludge [52]. Protein recovery and feed production can be achieved through gas-phase processing and metals can be recovered from sludge for reuse in various industries. Moreover, raw materials for pharmaceutical and human health products have also been recovered from dewatered sludge [50].

Although the technical possibilities are growing, there is still a lag in large-scale implementation for various reasons, including technical immaturity and non-technical bottlenecks. Resource recovery is often possible only on a small scale and quality control can be difficult to implement. Consequently, there is no competitive advantage with many recovered products compared against their conventionally produced counterparts. Dimensions of scale, consumer acceptance and stringent quality requirements can further inhibit the shift to material recovery from used water streams [52,47,50].

3.1.6. Food and biomass production (UCC5)

The Urban circularity challenge 5, can be linked to urban water in two directions and with both direct and indirect interdependencies. Water is an essential resource for growing food, and the presence of plants in the urban environment, in turn, affects the local water balance through evapotranspiration, infiltration and runoff mitigation. Localised food production systems can profit from recovered water for irrigation purposes and utilise fertiliser produced from used sewage sludge or household wastewater streams. Rainfed farming, an alternative option for irrigating urban crops, is another point of connection to UCC1, as disturbed precipitation patterns may cause difficulties in cases of drought or extreme rain events, if the urban farming system relies on rainwater harvesting as the primary source of water [53]. Restoring and maintaining the water cycle will have favourable impacts on any aspect of food and biomass production, like regular rainfall, increased humidity, moderate temperature peaks and flood reduction.

Improved micro-climates and soil moisture content also play a role in regulating the temperature within buildings (e.g. by green roofs or green walls) and in the environs, reducing the reliance on non-renewable energy sources for heating and cooling purposes [53-55], thus linking food and biomass production in the urban environment to the outer circle in Figure 2, through contributions to climate change mitigation and climate regulation.

3.1.7. Energy efficiency and recovery (UCC6)

Urban circularity challenge 6 has also been identified as having a strong two-way link to urban water, both to UCC1 and UCC2. Often described as the water-energy nexus, water and energy are interlinked in terms of resource use [56-57]. The water-energy nexus should be considered during the whole life cycle of resources and products. For instance, water is required for energy production, while energy is essential for water extraction, distribution, and treatment [58-59]. The residual heat in wastewater streams can be harnessed to contribute to improved energy efficiency. Greywater can also be reused for cooling purposes, reducing the need for fossil fuels used in conventional air conditioning units. The methane generated in sludge treatment facilities from anaerobic digestion is a valuable, closed-loop energy source that also contributes positively to the challenge of energy efficiency and recovery [60-62]. The recovery of organic residual streams from wastewaters can be a valuable resource for biogas production [48,63]. Anaerobic digestion of residuals of wastewater can enhance the production of carbon neutral biogas, methanol biodiesel or their bio-energies [64]. The production of bio-energies from organic residuals in wastewater requires large water treatment infrastructure, and is thus suitable only for larger urban areas.

Energy demand may be further reduced by implementing NBS for rainwater harvesting and management, for example by using vertical green infrastructure and green roofs. NBS can be applied to mitigate the issues related to climate change and ongoing urbanisation in line with the water-energy nexus [57]. The implementation of NBS from the category of urban greening (i.e., green roofs, green walls, parks, rain gardens etc.) helps to mitigate the urban heat island effect. It improves the thermal performance at building scale, thereby reducing the need for conventional air conditioning, and provides energy savings for the heating of buildings [19, 65-68].

3.1.8. Building system recovery (UCC7)

Urban circularity challenge 7 is related to urban water directly through UCC1, and indirectly through climate and resilience improvements related to NBS implementations from the urban water repository. Many of the NBS discussed in relation to urban water are directly connected to buildings, such as green roofs, green facades, living walls, and in some cases even building-integrated constructed wetlands. Further, conventional ways of building have contributed largely to the altered flow regime of rivers and urban streams and the disturbed water balance in urban catchments. The impervious paving alters runoff formation and may lead to increased pollution in stormwater runoff [69]. In this way, building systems are inextricably linked to the water cycle and urban water management on a smaller scale.

According to the path dependence theory, decisions from our past pave the way for future development [70-71]. When it comes to water in cities, the existing path has supported the development of linear systems over circular ones. Given the limited available urban space, it is evident that any given NBS solution should be conceived, designed, constructed and operated such that its contributions towards overcoming the seven circularity challenges are maximized. Consideration of the connections between these challenges and the way they relate to each other will offer a clearer picture of how to exploit synergies for a faster transition to circularity in cities.

3.1.9. Crucial challenges for water management

NBS for water management are traditionally implemented to increase water availability, improve water quality and mitigate water related risks [72]. Thus, UCC1 and UCC2 were identified as the central challenges in this context, and selected for a more in-depth analysis. However, hydraulic risk mitigation and water quality maintenance do not always adhere to circularity. Water management has a two-way influence on the economy and society and may be a decisive factor for environmental sustainability, and consequent economic development [73]. To facilitate future integration of NBS in circular urban schemes, there is a need to understand the different NBS units in a multidisciplinary perspective. The presently proposed integration of water into the different UCC (section 3.1) and the identification of key processes for water management (section 3.2.2), are expected to facilitate the transition towards circular urban schemes.

3.2. Achieving Circularity Challenges with NBS

3.2.1 Case-based assessment

In order to confirm the previous theoretical analysis, known examples of NBS in cities were listed and analysed. This included validating the interconnection between the key UCC1 and UCC2 for water management in circular cities, as well as with other UCCs. Table A1 (see annex A) summarizes examples of the described NBS units. The examples represent a wide range of applications, highlight the UCC addressed by the NBS examples, and give information of the several additional benefits that can be delivered by implementing a particular NBS. The listed real-life NBS confirm the validity of the UCC-NBS framework proposed. They highlight the circularity of NBS regarding the key water challenges (UCC1 and UCC2), and demonstrate potential synergies with other UCCs already successfully addressed by NBS. Moreover, compiling these examples has helped reveal current needs. Firstly, the need for a broader database in which NBS 'role in urban circularity is collected in a more structured way, including worldwide cases with particular attention given to full-scale systems. The need for such an NBS dataset is emerging and several datasets of NBS are being proposed, as recently reviewed [74] or as represented by the recent SNAPP dataset [75]. Secondly, the collection of examples should be accompanied, wherever possible, by quantification of their contribution to addressing circularity challenges, and the corresponding enabling processes, and as a result replace more and more simple qualitative evaluation. There is a need to provide a systematic overview of the functionalities of NBS and supporting units, as provided in this study, and demonstrate the importance of their implementation. It is also important to point out that NBS are often designed as a set of complementary and connected units [76] and each NBS unit can be essential, in some cases even with only one enabling process.

3.2.2 Enabling processes

Individual NBS and supporting units usually contribute to at least one or several urban circularity challenges (UCC). This is achieved by providing different physical, biological and chemical processes [77-78] or by enabling the reuse and recovery of water. The processes that certain NBS provide or employ are inherently connected with their purpose and contribution to achieving UCC. The most typical processes employed by NBS units for restoring and maintaining the water cycle (UCC1) are presented and described in Table 2, with examples of NBS units. Six enabling processes for UCC1 were selected: conveyance, infiltration, detention, retention, evapotranspiration and treatment.

Table 2. Enabling processes for achieving UCC1: restoring and maintaining the water cycle.

Enabling process	Process description*	NBS unit example
Conveyance	Transport of water.	Filter strip, bioswale, dry swale
Infiltration	Flow of water through the ground surface into soil or a porous medium.	Infiltration trench, infiltration basin, vegetated grid pavement
Detention	Temporary storage of precipitation which is en route to or in the stream/channel system, during or shortly after rainfall.	Intensive green roof, rainwater harvesting, (dry) detention pond, floodplain
Retention	Permanent storage of precipitation which is en route to or in the stream/sewer system.	(Wet) retention pond
Evapotranspiration	Water transferred from the soil to the atmosphere by evaporation and plant transpiration.	Bioretention cell (rain garden), urban forest, tree pits, extensive green roof
Treatment	Changing harmful or undesirable physical and chemical properties of water by removing harmful and undesirable substances and living organisms.	Treatment wetland, waste stabilisation pond

*[77-78].

In terms of water treatment, water recovery, and water reuse (UCC2), the processes most typically employed by NBS units are presented in Table 3, sedimentation, filtration, uptake by plants, biodegradation, photo-degradation, sorption, other treatments and reuse water. Water treatment and water recovery are not represented as stand-alone enabling processes, as they typically consist of a set of combined processes (*e.g.*, treatment train). Thus, all the enabling processes presented, except for the reuse of water, can be used to achieve water treatment or recovery (*e.g.*, sedimentation, filtration, etc.) by different NBS units and supporting units. This way, they are also related to the enabling process of water treatment presented in UCC1, where they can contribute to the restoration and maintenance of the urban water cycle. On the other hand, reuse of water enables the previously captured or/and treated water to be used again typically for irrigation purposes (*e.g.*, vertical green infrastructure & green roofs, greening interventions & green space) or groundwater recharge (e.g., infiltration basin, infiltration trench).

Table 3. Enabling processes for achieving UCC2: water - treatment, recovery, and reuse.

Enabling process	Process description*	NBS unit example
Sedimentation	Process of settling and depositing suspended matter in water by gravity.	Infiltration basin, Waste stabilisation pond
Filtration	Process of passing a liquid through a filtering medium for the removal of suspended or colloidal matter.	Filter strip, riparian buffer, treatment wetland
Uptake by plants	Transfer of substances from the environment to plant tissue/structure.	Bioretention cell (Rain garden), phytoremediation
Biodegradation	Biochemical transformation of substances using microorganisms, mostly bacteria, to stable end products.	Treatment wetland, waste stabilisation pond
Photo-degradation	Process of degradation of substances exposed to sunlight ultraviolet radiation	(Wet) Retention pond / Waste stabilisation pond
Sorption	Includes the processes of adsorption and absorption by which some substances become attached to another (soil, sludge or plants).	Intensive green roof, anaerobic treatment
Other treatments	Phosphorus precipitation; Ammonia stripping; Chemical disinfection; Pyrolysis; Advanced oxidation	Supportive units
Reuse of water	To use water again especially in a different way or after recovery/treatment.	Productive garden, street trees

*[88-89].

3.2.3 Assessment of Total Circularity Scores

Based on the aforesaid processes (Tables 2 and 3) the 51 NBS and 10 supporting units [20] were semi-quantitatively ranked based on (described in section 2), the extent to which they can contribute to addressUCC1 and UCC2. The qualitative assessment of NBS units provides a systematic overview of their functionalities and demonstrates the importance of their implementation. For each NBS unit and enabling process, a mark value of 3, 2 or 1 was assigned when the NBS unit addresses, contributes or could potentially contribute depending on the design, respectively, to the UCC1 and UCC2. To facilitate the interpretation of these results a shorter list of 12 selected representative NBS covering different sub-categories was formed (as can be seen in Table 4). The full dataset is included as Table A2.

Based on this semi-quantitative analysis, the NBS units with the highest total circularity score were river restoration, reconnection of oxbow lake and floodplain (restoration units), treatment wetlands (remediation, treatment, and recovery unit) and riparian buffer (rainwater management unit). Considering the total circularity score, 8% of the NBS units were assigned a score higher than 20 (out of a maximum of 36), which can be considered as highly contributing units, while 37 % achieved a score between 10 and 20, regarded as units with medium impact. Finally, among the 51 NBS units, 55% (28 units) achieved a score lower than 10. Thus, if implemented as stand-alone units, they are anticipated to have a limited contribution to UCC1 and UCC2. All the supporting units (a total of 10) used for rainwater management, remediation, treatment, and recovery achieved a score lower than 10 and thus, have a low impact on UCC1 and UCC2 on a stand-alone basis.

Rainwater management units are ranked with low to medium impact. Among them, the riparian buffer and the bioretention cell (or rain garden) are the most effective ones to face the UCC1 and UCC2, whereas infiltration trench and dry swale are found to be the least effective. The riparian buffer and the bioretention cell can better tackle restoring and maintaining water cycle challenge UCC1 because the presence of vegetation enables processes such as detention, evapotranspiration, and treatment. The riparian buffer, in particular, can largely contribute to infiltration, conveyance and detention, and is the most effective NBS unit to face UCC1. Evaluating the contribution of these four NBS units to UCC2 we find that the main difference stems from the uptake by plants in the treatment enabling processes. The riparian buffer and the bioretention cell are also able to address UCC2, while the infiltration trench and the dry swale have only potential contribution to UCC2.

Vertical green infrastructures and green roofs are determined as units with low to medium impact on UCC1 and UCC2. Intensive green roofs are ranked as the highest, and extensive green roofs as the lowest. Though both versions of green roofs address the UCC1 equally, extensive green roof's contribution to UCC2 is limited compared to intensive green roofs. Intensive green roofs have higher detention and treatment due to a deeper soil layer, greater variety of vegetation, and installation and maintenance operations like irrigation and fertilisation. Further, intensive green roofs enable treatment processes like filtration, microbiological treatment and uptake by plants and sorption. Finally, intensive green roofs can be irrigated with treated water, thus contributing to water reuse [79]. Thus, UCC2 is addressed better by intensive roofs. This example illustrates that the contributions of certain NBS to the UCC 1 and 2 can largely differ, based on the NBS design.

Remediation, treatment, and recovery units have a wider range in terms of contribution to UCC1 and UCC2 because high, medium, and low impact units coexist in this group. Aerobic and anaerobic treatment units can provide only microbiological treatment whereas treatment wetlands also enable processes like sedimentation, filtration, uptake by plants, sorption, and degradation by solar radiation [42]. Besides, treatment wetland is the most effective treatment because it provides detention, retention and evapotranspiration of water. Consequently, these units have noticeably different contributions to both UCC1 and UCC2.

River restoration units are composed of high- and low-contributing units simultaneously. River restoration is found to be a highly contributing NBS unit with conveyance, infiltration, detention, evapotranspiration and treatment functionalities, thus contributing largely to UCC1. Additionally, river restoration units can face UCC2 through all the wastewater treatment enabling processes. On the other hand, coastal erosion control can provide only conveyance. Therefore, its role as a single unit is only transporting water, and it needs to be combined with other units to address UCC1. Moreover, they are not considered relevant in terms of waste and water treatment, recovery and reuse.

Greening intervention units are ranked with medium impact whereas units for food and biomass production are determined to have lower or medium impact. Large urban parks as a greening intervention and productive garden as food and biomass production units are mostly important for UCC1 through infiltration, detention and evapotranspiration. However, they are not the most effective in addressing UCC2 because they lack water treatment capacity. Nevertheless, their potential should not be disregarded, due to their function in enabling the reuse of the treated water. This calls for the relevance of understanding which inputs and outputs are needed or can be used among the different units.

Every process realised or facilitated by NBS which achieves UCC1 has the potential to transform water into a reusable resource. Water conveyance achieves circularity when it is redirected to gardens, cultivated areas, or the subsoil, where it is stored for future use or recharges surface water bodies, preserving a minimum flow in the face of prolonged drought, increasing the water storage capacity in urban soils and enhancing the respective ecosystem service [80]. Infiltration, similarly, increases the water stock in the subsurface water bodies. Detention, when paired with reuse, can be effective from a circular economy perspective, and retention can achieve both the circularity goals of infiltration and detention systems. When evapotranspiration coincides with crop production or useful plant growth the water cycle becomes a circular economy tool. Water reuse is made possible by using NBS treatment to achieve adequate water quality (UCC2). NBS which address (waste)water treatment by sedimentation, filtration, microbiological treatment and degradation of contaminants or water recovery, thus support addressing circularity. Moreover, by reusing water to feed NBS, circularity is achieved by closing the loop and recovering water and potentially nutrients cycling back to UCC1 and the preservation of the water cycle. Apart from aspects relating to the hydrological cycle, water reuse, and treatment, a water-centered perspective of urban circularity must also consider the matters of nutrient recovery, material recovery, food and biomass production, the water-energy nexus, and examining the built-up environment.

The NBS discussed here are highly effective and promising systems to address the UCC, but their contributions to circularity will rely heavily on the extent of their implementation, the consistency and appropriateness of their operation and maintenance schemes, and, perhaps most importantly, their acceptance and recognition by citizens and the society at large. The proposed semi-quantitative categorisation of NBS units (Table 4 and Table A2) is intended as a tool to support this transition.

The quantification of other types of ecosystem services, especially those related to biodiversity, social and economic aspects, remains an open issue under research. For example, the role of NBS in psychological health and the overall well-being has recently been studied [81]. There is a distinct lack of examples in which ecosystem services or co-benefits are quantified, while most of the time they are indicated qualitatively, or when quantified, they are hardly comparable due to the use of several different evaluation frameworks and databases [82-86]. This could be related to the lack of standardization in monitoring NBS performance and NBS benefits. However, this will hopefully improve with the new handbook published by the European Commission [87], which provides a comprehensive NBS impact assessment framework and a robust set of indicators and methodologies to help decision-makers and practitioners assess the impact of NBS [88]. Ecosystem service evaluation [89] and monetisation (e.g., [90]) can also play a relevant role.

Table 4. Case-based (Table A1) qualitative assessment of the 12 selected NBS units.

Sub-category	NBS unit	Total circularity score[1,2]	URBAN CIRCULARITY CHALLENGE														
			UCC1: Restoring and maintaining the water cycle							UCC2: Water - treatment, recovery, and reuse							
				Enabling process							Enabling process						
			UCC1 mark[3]	Conve-yance	Infiltration	Detention	Retention	Evapotrans.	Treatment	UCC2 mark[3]	Sedimentation	Filtration	Uptake by plants	Bio-degradation	Photo-degradation	Sorption	Reuse of water
Units for rainwater management	Infiltration trench	7	3		3				1	1		1		1		1	1
	Bioretention cell (Rain garden)	16	3		1	3		3	3	3	3	1	3		1	1	
	Dry swale	6	3	3	2				1	1		1					
	Riparian buffer	19	3	3	3	3		3	3	3	1	2	3			1	
Vertical Green Infrastructure & Green Roofs	Extensive green roof	6	3			1		3	1	1			1			1	
	Intensive green roof	15	3			3		3	2	2		1	2	2		2	2
Remediation, Treatment & Recovery	Treatment wetland	21	3			3	2	3	3	3	2	3	2	3	1	2	
	Anaerobic treatment (for nutrient, VFA & methane recovery)	3	3						3	3				3			
River Restoration	River restoration	24	3	3	3	3		3	2	2	2	2	2	2	2	2	
	Coastal erosion control	2	2	2													
Greening intervention + (Public) Green Space	Large urban park	14	3		3	3		3	1	3		1	1				3
NBS units for food & biomass production	Productive garden	12	3		3	2		3	1	3			1				3

For each NBS unit and enabling process, a mark of 3, 2 or 1 is assigned when the NBS unit, respectively, addresses, contributes or could potentially contribute depending on the design to the UCC1 and UCC2.
[1] The total circularity score achieved by an NBS unit for both UCC1 and UCC2 is calculated as the sum of all awarded marks, excluding the enabling process "Treatment" within UCC1.
[2] NBS units are classified into 3 classes of contribution based on the total circularity score for UCC1 and UCC2: high >20, medium 20-10, low <10.
[3] UCC1 or UCC2 mark indicates the maximum mark for one of the enabling processes, that the particular unit was assigned.

Despite the recent advances in NBS concepts and deepening insights we now have on the benefits of NBS for a circular economy, there is a gap between the implementation and fundamental understanding of their role in a circular city. Only 70 out of the 167 nationally determined contributions submitted under the Paris Agreement include NBS actions, the majority of which are in low-income countries [91]. However, it should also be noted that in more than 20 tropical countries, NBS implementation is relatively high, putting them on track to achieving carbon neutrality before 2030 [15,69]. Thus, the potential of NBS to provide multiple economic, environmental and social benefits is not yet fully utilised [92].

To overcome the different barriers identified in this study, we reiterate a series of recently proposed actions [11,93]: (i) raise awareness on nature's value, through collaboration and experience exchange across different stakeholders, facilitated by governments, civil society organisations, and the private sector, (ii) integrate NBS into climate adaptation plans and circular economy strategies, (iii) encourage investment in NBS, by developing new funding streams and models that can support long-term investment, including private sector actors, modifying governmental policies, subsidies, and public investments and providing better incentives for private investors to finance NBS projects, and (iv) integrate NBS in financial conditions, procurement, industry standards and other policies to link the current challenges with the available solutions and expertise.

Circularity is a new way of planning water management by use of multiple and interconnected solutions aimed at restoring or creating water, materials and energy cycles [94-96]. In this respect, the present work provides a multidisciplinary overview of different NBS and tries to raise the awareness of the potential of NBS to address multiple urban circularity challenges.

4. Conclusions

This collaborative paper provides a water-centric perspective on how to address the CA17133 seven urban circularity challenges (UCC), while bolstering resilience and enabling circularity with NBS. The interconnections between the different UCC were discussed and demonstrated with case studies selected based on the expertise and knowledge available in the workgroup.

The multifunctionality of the 51 NBS and 10 supporting units have been assessed and linked with the UCC and their interconnections. The potential applicability of NBS units and supporting units to address the two water-centered UCCs, UCC1 and UCC2, was assessed using a semi-quantitative methodology. Among the 61 units, the NBS circularity scoring identified 3 highly contributing units and 20 medium contributing units towards addressing the UCC. The provided semi-quantitative categorisation can be used as a tool to support wider implementation of the NBS to address UCC common for many cities. The proposed circularity ratings, which identify critical processes for water management, are anticipated to help in the adoption of NBS to achieve sustainable urban water management.

In order to better confront the varied and complex difficulties presented by the UCCs, the provided interdisciplinary, collaborative approach made use of the participants' knowledge, experience, and expertise relating to water management and NBS. However, our analysis reveals that the multifunctionality of NBS in a multidisciplinary perspective, is not fully understood. Current NBS knowledge has to be broadened beyond professionals to include non-specialists and key stakeholders. By considering practical, real-world examples and incorporating a diverse group of informants, comparable approaches involving non-experts can be effective in preventing an unduly techno-centric and siloed vision of water management. Accordingly, we recommend to focus further research on the quantification of ecosystem services (related to biodiversity, social and economic aspects), in order to bridge the gap between the implementation and fundamental understanding of NBS role in a circular city.

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Appendix A

Table A1. Case-studies, models, theories, and lab-scale of representative NBS units, exemplifying their contribution to the urban water management and the circularity challenges (UCC).

NBS[1]	Type	Location	Urban Circularity challenges.[2]	Other contributions and Ecosystem Services	Ref.
Infiltration basin (NBS_tu)	Case-study	Ljubljana (SI)	UCC1 UCC2		[97]
Infiltration trench (NBS_tu)	Case-study	Málaga (ES)	UCC1 UCC2	Amenity Biodiversity support Construction community space (Playscape) Educational value	[98]
Filter drain (NBS_tu)	Case-study	Various Austrian cities (AT)	UCC1 UCC2	Improved microclimate Taking pressure off water collection and treatment systems	[99]
(Wet) Retention pond (NBS_tu)	Case-study	Ljubljana (SI)	UCC1 UCC2 UCC6	Biodiversity support Education Recreation	[100]
(Dry) Retention pond (NBS_tu)	Case-study	Carugo (IT)	UCC1	Amenity Biodiversity support	[101]
Bioretention cell Rain garden (NBS_tu)	Case-study	Sassuolo (IT)	UCC1 UCC2	Amenity Improved microclimate	[101]
	Case-study	Turin (IT)	UCC1 UCC2	Amenity Education	[102]
Bioswale (NBS_tu)	Case-study	Gdynia (PL)	UCC1 UCC2	Amenity	[103]
Riparian buffer (NBS_tu)	Case-study	Scandolara (IT)	UCC1 UCC2	Biodiversity support	[104]
	Case-study	Mściwojów (PL)	UCC1 UCC2 UCC7	Biodiversity support	[105]
Extensive green roof (NBS_tu)	Case-study	Rende (IT)	UCC1 UCC2 UCC6 UCC7	Amenity Biodiversity support Building thermal performances Education Improved microclimate	[40, 106-107]

Intensive green roof (NBS_tu)	Case-study	Treviso (IT)	UCC1 UCC2 UCC6		[79]
	Case-study	Wrocław (PL)	UCC1 UCC2	Amenity Education Biodiversity support	[108]
Treatment wetland (NBS_tu)	Case-study	Gorla Maggiore (IT)	UCC1 UCC2	Amenity Recreation Biodiversity support	[89,109-110]
	Case-study	Lesvos (GR)	UCC2 UCC3 UCC5 UCC6	Biodiversity support	[24,95]
	Case-study	Mściwojów (PL)	UCC1 UCC2 UCC3 UCC7	Biodiversity support	[105]
	Case-study	tba	UCC2 UCC3 UCC5 UCC6	Being gender neutral Biodiversity support Improved microclimate Reducing carbon footprint Reducing noise pollution Storing nutrients from urine in plant biomass Working off-the-grid and being Water & energy autonomous	[111]
	Case-study	Lloret de Mar (ES)	UCC1 UCC2 UCC3 UCC6	Amenity Biodiversity support Improved microclimate Education	[94,112]
	Case-study	Nimr (OM)	UCC2 UCC3 UCC4 UCC5 UCC6	Biodiversity support Carbon emissions mitigation Improved microclimate	[96]
	Case-study	Mashhad (IR)	UCC2 UCC4	Reducing carbon footprint	[113]
Waste stabilization pond (NBS_tu)	Case-study	Vélez-Málaga (ES)	UCC2 UCC4		[114]

Composting (NBS_i)	Model	Nimr (OM)	UCC3 UCC4		
Phytoremediation (NBS_i)	Case-study	Iwiny (PL)	UCC2 UCC7		[115]
	Model/ theory	EU	UCC7		[116]
	Model/ theory	EU	UCC2		[117]
River restoration (NBS_i)	Case-study	Łódź (PL)	UCC1 UCC2	Biodiversity support	[118]
	Model	Alexandria (EG)	UCC2	Biodiversity support Public health protection	[119]
Floodplain (NBS_i)	Case-study	Poznań (PL)	UCC1	Recreation Thermal regulation	[120]
Diverting and deflecting elements (NBS_i)	Case-study	Jimera de Líbar (ES)	UCC1		[114]
Soil reinforcement to improve root cohesion and anchorage (NBS_i)	Case-study	Prov. Málaga (ES)	UCC1		[114]
Green corridors (NBS_su)	Case-study	Nijas (ES)	UCC1		[114]
Street trees (NBS_su)	Case-study	Malaga (ES)	UCC1		[114]
Pocket/garden park (NBS_su)	Case-study	Wrocław (PL)	UCC1	Biodiversity increase Aesthetic	[121]
Green transition zones (NBS_su)	Case-study	prov. Málaga (ES)	UCC1		[114]
Rain Water Harvesting (S_u)	Case-study	Hedensted (DK)	UCC1 UCC2 UCC6	Heat island reduction	[24]
	Case-study	Rende (IT)	UCC1 UCC2 UCC4		[106]
	Lab-scale	Rende (IT)	UCC1 UCC2 UCC4		[122-123]

[1] NBS units (NBS_u), which includes NBS spatial units (NBS_su) and NBS technological units (NBS_tu); NBS interventions (NBS_i), which include NBS soil and river interventions (NBS_is and NBSir); and Supporting Units (S_u)

[2] Urban circularity challenges: UCC1, Restoring and maintaining the water cycle; UCC2, Water & waste treatment, recovery and reuse; UCC3, Nutrient recovery and reuse; UCC4, Material recovery and reuse; UCC5, Food and biomass production; UCC6, Energy efficiency and recovery; UCC7, Building system recovery.

Table A2. Case-based (Table A1) qualitative assessment of the NBS and supportive units*.

Sub-category	NBS unit	Total circularity score[1,2]	URBAN CIRCULARITY CHALLENGE															
			UCC1: Restoring, maintaining the water cycle							UCC2: Water - treatment, recovery, and reuse								
				Enabling process							Enabling process							
			UCC1 mark[3]	Conveyance	Infiltration	Detention	Retention	Evapotranspiration	Treatment	UCC2 mark[3]	Sedimentation	Filtration	Uptake by plants	Bio-degradation	Photo-degradation	Sorption	Other treatment	Reuse of water
Units for rain water management	Infiltration basin	9	3		3				2	2	2	1		1		1		1
	Infiltration trench	7	3		3				1	1		1		1		1		1
	Filter strips	10	3	3					2	2	2	2	2			1		
	Filter drain	8	3	3					2	2	1	2		1		1		
	(Wet) Retention pond	13	3			1	3	3	2	2	2		1	1	2			
	(Dry) Detention pond	7	3			3			2	2	2		2					
	Bioretention cell (Rain garden)	16	3		1	3		3	3	3	3	1	3		1	1		
	Bioswale	14	3	3	2			3	3	3	1	1	3	1				
	Dry swale	6	3	3	2				1	1		1						
	Tree pits	13	3		1	3		3	2	3		1	2					3
	Vegetated grid pavment	11	3		3			3	2	2		2	2			1		
	Riparian buffer	19	3	3	3	3		3	3	3	1	2	3			1		
Vertical Green Infrastructure & Green Roofs	Soil/ground-based green facade	6	2					2	1	3			1					3
	Wall-based green facade	9	2					2	1	3		1	1	1		1		3
	Pot-based green facade	9	2					2	1	3		1	1	1		1		3
	Vegetated pergola	4	1					1		3								3
	Extensive green roof	6	3			1		3	1	1			1			1		
	Intensive green roof	15	3			3		3	2	2		1	2	2		2		2
	Semi-intensive green roof	12	3			2		3	2	2		1	2	1		1		2
	Mobile green and vertical mobile garden	6	1			1		1	1	3			1					3
Remediation, Treatment & Recovery	Treatment wetland	21	3			3	2	3	3	3	2	3	2	3	1	2		
	Waste stabilisation pond	16	3			3	2	3	3	3	3			3	2			
	Composting	0																
	Bioremediation	4	1		1			1	1	1			1	1				

	Phytoremediation	4	1		1			1	1	1			1	1				
	Anaerobic treatment (for nutrient, VFA & methene recovery)	3	3						3	3				3				
	Aerobic (post) treatment (for water recovery)	3	3						3	3				3				
(River) Restoration	River restoration	24	3	3	3	3		3	2	2	2	2	2	2	2	2		
	Floodplain	20	3	3	3	3		3	2	2	2	2	1	1	1	1		
	Diverting and deflecting elements	1	1	1														
	Reconnection of oxbow lake	24	3	3	3	3		3	2	2	2	2	2	2	2	2		
	Coastal erosion control	2	2	2														
Soil and Water Bioengineering	Soil improvement and conservation	5	1		1	1			1	1		1		1		1		
	Erosion control	6	1	1	1			1	1	1		1	1			1		
	Soil reinforcement to improve root cohesion and anchorage	1	1		1													
	Riverbank engineering	2	1					1	1	1			1					
Greening intervention + (Public) Green Space	Green corridors	14	3		3	3		3	1	3		1	1					3
	Green belt	14	3		3	3		3	1	3		1	1					3
	Street trees	12	3		1	3		3	1	3		1	1					3
	Large urban park	14	3		3	3		3	1	3		1	1					3
	Pocket/garden park	12	3		2	2		3	1	3		1	1					3
	Urban meadows	13	3		3	3		2	1	3		1	1					3
	Green transition zones	9	2		1	1		2	1	3		1	1					3
NBS units for food & biomass production	Aquaculture	1								1								1
	Hydroponic and soilless technologies	2	1						1	1			1					1
	Organoponic / Bioponic	3	1						1	1			1			1		1
	Aquaponic farming	6	2						2	2	1		2	1				2
	Photo Bio Reactor	3	2						2	2				2	1			
	Productive garden	12	3		3	2		3	1	3			1					3
	Urban forest	11	3		3	3		3	1	1			1					1
	Urban farms and orchards	12	3		3	2		3	1	3			1					3

Sub-category	Supporting unit	Total circularity score[1,2]	UCC1 mark[3]	Conveyance	Infiltration	Detention	Retention	Evapotranspiration	Treatment	UCC2 mark[3]	Sedimentation	Filtration	Uptake by plants	Bio-degradation	Photo-degradation	Sorption	Other treatment	Reuse of water
Units for rain water management	Rain Water Harvesting	4	3			3			1	1	1							
	Detention vaults and tanks	4	3			3			1	1	1							
Remediation, Treatment & Recovery	Phosphate precipitation (for P recovery)	3	3						3	3							3	
	Ammonia stripping (for N recovery)	3	3						3	3							3	
	Disinfection (for water recovery)	6	3						3	3					3		3	
	Biochar/Hydrochar production	3	3						3	3							3	
	Physical unit operations for solid/liquid separation	6	3						3	3	3	2				1		
	Membrane filtration	3	3						3	3		3						
	Adsorption	3	3						3	3						3		
	Advanced Oxidation Processes (AOP)	3	3						3	3							3	

*For each unit and enabling process, a mark of 3, 2 or 1 is assigned when the unit, respectively, addresses, contributes or could potentially contribute depending on the design to the UCC1 and UCC2.

[1]The total circularity score achieved by a unit for both UCC1 and UCC2 is calculated as the sum of all awarded marks, excluding the enabling process "Treatment" within UCC1.

[2]Units are classified into 3 classes of contribution based on the total circularity score for UCC1 and UCC2: high >20, medium 20-10, low <10.

[3]UCC1 or UCC2 mark indicates the maximum mark for one of the enabling processes, that the particular unit was assigned.

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Nature-based units as building blocks for resource recovery systems in cities

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Abstract: Cities are producers of high quantities of secondary liquid and solid streams still poorly utilized within urban systems. In order to tackle this issue, there has been an ever-growing push for more efficient resource management and waste prevention in urban areas, following the concept of a circular economy. This work provides a characterization of urban solid and liquid resource flows (including water, nutrients, metals, potential energy, and organics), which pass through selected Nature-Based Solutions (NBS) and Supporting Units (SU), expanding on that characterization through the study of real-life cases. In particular, this paper presents the currently implemented NBS units for resource recovery, the applicable solid and liquid urban waste streams and the SU dedicated to increase the quality and minimize hazards of specific streams at the source level (e.g., concentrated fertilizers, disinfected recovered products). Recovery efficiency of systems, where NBS and SU are combined, operated at micro or meso-scale and applied at Technology Readiness Levels higher than 5 is reviewed. The importance of collection and transport infrastructure, treatment and recovery technology and (urban) agricultural or urban green reuse on the quantity and quality of input and output materials is debated, also regarding the current main circularity and application challenges.

Key-words: Circularity challenges; Nature based solutions; Supporting units; Urban streams; Circular cities

1. Introduction

Cities are centres of human and economic activity and, in its flurry, are producers of high quantities of discarded materials and products, effectively functioning as concentrators of natural resources, perpetuating the current linear system of "take-make-dispose" (EMF - Ellen MacArthur Foundation, 2017). In order to combat this huge resource consumption, there has been an ever-growing push for the adoption of better resource management and waste prevention in urban areas, going in line with the concept of Circular Economy (Zeller et al., 2019). This paper is a product of an interdisciplinary cooperation among researchers from all 28 EU countries and 11 third countries within the EU-funded COST Action 17133 "Implementing nature-based solutions for creating a resourceful circular city" (https://www.cost.eu/actions/CA17133/) that attempts to contribute to this discussion of implementation of Circular Economy in cities, particularly by the use of specific technologies, interventions, and units based on natural principles.

The definition of Circular Economy provided in the first paper of the COST Action Circular City (Langergraber et al., 2020) goes in hand with previous definitions provided by other sources (Fratini et al., 2019; Kirchherr et al., 2017), describing it as an economic system that aims at minimizing waste and input of energy and returns them as many resources as possible. In order to do this, the different economic systems must firstly bear in mind to minimize resources input and waste, gas emissions, and energy leakage. In urban environments, this could be achieved by slowing, closing, and narrowing both energy and material (water, nutrients, commodities) loops in such a way that the amount of waste generated is minimal or avoided at all (Babí Almenar et al., 2021; Langergraber et al., 2020).

However, the implementation of circularity in urban areas comes with added challenges which need to be addressed (Fig. 1). Paiho et al. (2020) attempted to develop a comprehensive list of these challenges, which were subdivided into four main categories:

- On the "Business" category; the authors named the insufficient market demand for the majority of secondary materials, the insufficient funding for institutions which develop this type of solutions, the high investment costs usually associated with circular economy solutions, the vested interests of business actors and the fact that the product prices usually do not take environmental costs into account;
- On the "Policy" category; the challenges come in the form of lack of established subsidies/taxes to encourage circular resource use, the administrative fragmentation that makes legal procedures more complex, the lack of proper policy, and regulation for the application of certain solutions, and the usual lack of long-term strategies;
- On the "Technical" category; the challenges were on the technological lock-in in linearity (as existing infrastructure does not incorporate circular design or integrated nexus solutions), the insistence on linear design (including planned obsolescence), the need for additional technological innovation (especially in developing countries), and the limited separation of nutrients from different sources in conventional city waste treatment (bio-based nutrients with potentially toxic metals, for example) leading to toxicity and poor resource quality, preventing it from returning to the value chain;
- On the "Knowledge" category; the main challenges in the development of circularity are the lack of consumer awareness and demand for circular economy solutions, the dominance of linear thinking (wariness of reused products and materials, perception that new products are of higher-status), the ambiguity of the concept of circularity to public and business actors, the confusion on the concept leading to a narrow interpretation unsuitable for an adequate transition, and, ultimately, a lack of performance metrics to measure circularity.

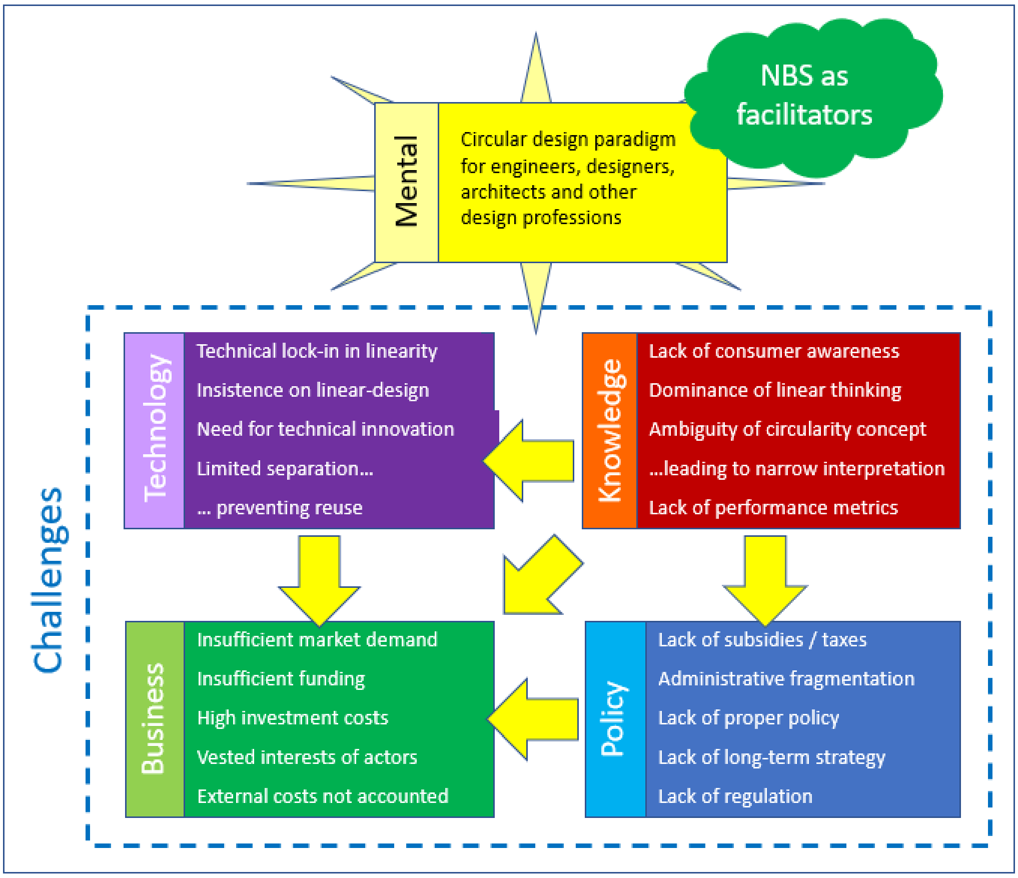

Figure 1. Challenges to the implementation of circularity in urban areas (Paiho et al., 2020) and the critical role of the mental category – a new circular design paradigm - to address them, using nature-based solutions as facilitators.

In addition, a fifth "mental" category (Fig. 1) is the necessary shift from the prevailing linear approach in problem-solving towards a more holistic, circular design approach (Schönborn & Junge, 2021). Engineers, designers, architects and other design professions are playing a key role in creating the built environment. In the traditional linear design process, effects that occur outside of the system borders, are generally considered as a separate problem. As a consequence, it is in the best case tackled in a separate design process, or else directly handed over to nature (which mostly means that it is not addressed at all). This practice is inherently prone to create new environmental challenges, as the development of wastewater management in the last two centuries demonstrates (Schönborn & Junge, 2021). The development of a circular design paradigm for the above-mentioned professions must therefore also be part of the development of circularity practices.

To deal with these circularity challenges, Langergraber et al. (2020) proposed to apply the concept of a Circular City as a basis for the application of Nature-Based Solutions (NBS). By establishing simultaneously cost-effective, resource efficient, and locally adapted solutions, NBS can serve as application tools of circular economy within cities (Langergraber et al., 2020; Nika et al., 2020). In general, by their definition, NBS can serve both as replacement for the grey infrastructure which is based on linear principles and also as complementary systems which can help in the transition towards circularity (Kisser et al., 2020; Nika et al., 2020). The COST Action Circular City also attempted to define the specific circularity challenges in cities approachable by NBS. These technical challenges were defined by Atanasova et al. (2021) as following:

- Preserving natural resources by reducing their import;
- Minimizing waste production by using resources in cycles.

Atanasova et al. (2021) as well Langergraber et al. (2021) attempted to specify these challenges towards the specific resource streams treated by NBS (water, food, materials, energy). To that extent, a detailed list of urban circularity challenges (UCC) could be obtained as follow:

1. Restoring and maintaining the water cycle (by rainwater management) (UCC1);
2. Water and waste treatment, recovery and reuse (UCC2);
3. Nutrient recovery and reuse (UCC3);
4. Material recovery and reuse (UCC4);
5. Food and biomass production (UCC5);
6. Energy efficiency and recovery (UCC6);
7. Building system recovery (UCC7).

Additionally, however, NBSs can provide other advantages in urban settings, such as the enhancement of their environmental and ecological status, addressing the demand of the populations for natural resources, climate change mitigation and adaption, among others. In this way, human well-being is improved and the societal challenges of urban living are ameliorated, ensuring approval of the local populations (Nika et al., 2020). This entire process, therefore, ensures a systemic transition towards circularity in cities which guarantees not just economic and environmental harmony, but also societal support.

This movement towards circularity will promote the recovery and the closing of the loop of both water within cities and several nutrients as well as other resources carried by city waters (Neczaj & Grosser, 2018). The water itself can be recovered, reclaimed, and reused, in order to obtain a more sustainable water management system (Sgroi et al., 2018). Many of the water flows within cities are characterized by high content in carbon, nitrogen, phosphorous, and potassium (Venkata Mohan et al., 2020). Additionally, other elements usually not aligned with natural systems, such as metals, pharmaceuticals, pesticides, etc., can also be found in unsuitable concentrations, which require treatment and recovery (Kisser et al., 2020). The origins of these flows are primarily derived from management systems, namely sewage systems, rubbish bins, and exhaust pipes, that are ubiquitous in modern cities. Therefore, these secondary resource streams (urban and industrial wastewater, municipal solid waste, and gaseous effluents) are the key aspect in the development of a solid closed loop economic model confined to city boundaries (Kisser et al., 2020; Venkata Mohan et al., 2020). For instance, Zeller et al. (2019), after an analysis of the waste flows of various sources in the city-region of Brussels, concluded that wastes with the lowest market value accumulated at high density and high unit cost and transportation by treatment (such as municipal solid waste or organic waste) are more suited for local material recycling and energy recovery than high market value waste such as metal and glass. Thus, the highest circular economy valorization potential for these secondary bioresource flows, that is, organic waste containing nutrients and biomass, comes in the form of technologies capable of integrating these waste flows within the urban metabolism.

Accordingly, in 2017 urban populations as such are responsible for 75% of the consumption of natural resources, 50% of the generation of global waste, and 60-80% of overall greenhouse gas emissions (EMF - Ellen MacArthur Foundation, 2017). For this reason, it is critical to achieve an adequate balance in which this expenditure is minimized and as much of the material and energy outflows involved in the urban lifestyle are reintroduced into the urban environment as novel inputs.

In order to determine an adequate balance of the material and energy flows in organic waste and wastewater systems in urban areas to ensure circularity, firstly these flows must be identified and studied, both as inputs and outputs. The bibliography on this matter still considerably lacks in characterization of these flows. This is primarily due to the absence of a uniform characterization model for resource flows in urban areas and a lack of defined geographical boundaries to limit the urban areas (Paiho et al., 2020). Urban metabolism studies have used several different approaches, from Material Flow Analysis

(MFA), Life-cycle Assessment (LCA), Input-output (IO) analysis, Cost-Benefit Analysis (CBA), spatio-temporal modelling with geographic information system analysis, and many others (Corona et al., 2019; Wielemaker et al., 2019; Paiho et al., 2020; Spuhler et al., 2020). Some studies have tried to perform flow balance of the waste/resource flows within urban areas and their surrounding regions (Gao et al., 2021; Zeller et al., 2019), but mainly they consider the entire waste sector and end up not focusing on the specific material and energy flows of organic waste and wastewater management. Alternatively, other studies focused on some of the specific technologies applied in urban areas, such as sanitation systems (Spuhler et al., 2020; Wielemaker et al., 2019), which defined the following inputs: total phosphorous (P), total nitrogen (N), potassium (K), total solids, and water. Water is considered as an increasingly scarce commodity in urban areas due to human and industrial pressure, which needs to be saved or reused. Both P and N were defined as important macronutrients, while total solids were in turn used as a proxy from which either energy could be recovered in the form of biochar or biogas, or organic matter could be recovered as a soil amendment. However, P, N, and total solids can also be considered pollutants, as their mismanagement and accumulation in water bodies can lead to algal blooms, eutrophication, and hypoxic dead zones (Venkata Mohan et al., 2020).

One example of an analysis of a coupled urban-agricultural system and the material flows of P and N is provided by Firmansyah et al. (2017). Overall flow analysis showed that the agricultural system was a significant source of N and P nutrients lost through erosion/run-off and leaching. The urban systems also had considerable negative impact on this isolated ecosystem local due to N and P losses from domestic waste and wastewater by leaching and atmospheric emission. The authors of this study concluded that the nutrient management was clearly unbalanced. Approaches to rebalancing the situation within the island come mostly by changing the current sanitation system, ensuring the retrieval of N and P present in domestic waste and runoff for application in all subsystems.

Based on the information gathered on the definition of the input and output flows of the bioresources and equivalent materials even in circular systems, it must be understood that a circular urban system will never be fully self-sufficient: much of the nutrients in cities such as nitrogen and phosphorous enter in the form of food, which is heavily produced outside city boundaries (Firmansyah et al., 2017; Paiho et al., 2020; Zeller et al., 2019). Although some food production can be developed inside cities in the form of urban farms or equivalent units (Paiho et al., 2021), the import of food is still and will remain dominant. Therefore, in order to achieve a circular bioresource system in cities, it must be ensured that the flows of nutrients must be subdivided into separate fractions: i) one that will remain in the city environment and helps in subsisting both the natural ecosystem and some of the human activities; and ii) another fraction must be adequately exported out of the city for agricultural and other purposes. The recovered nutrients can be transformed into composts or fertilizers with high nitrogen (N) and phosphorus (P) content. In this paper we discuss NBS supporting the flows of nutrients in the city environment while the fraction of flows for agriculture and other purposes outside the city borders is not addressed.

Considering the necessity of maintaining a sustainable management of water, nutrients, and other meaningful flows present in the urban water and biowaste sector, it becomes obvious that novel or already used technologies need to be evaluated, not only on their efficiencies and economic output, but also on their potential to separate and recover these elements in the same or novel forms to achieve circularity. In that way, both environmental and economic value can be derived, and a successful transition of this sector towards circularity can not only be possible, but attractive. NBS methodology of which the development of a holistic, circular approach for problem solving is a part of, is extremely interesting, as the inherent focus on resource recovery ensures an improved management of water, carbon, nutrients, energy, and potentially other elements that can be used in interconnected systems (Nika et al., 2020). It may become the key facilitator for the implementation of circularity (Fig. 1). Contaminants (pathogens, organic micro-pollutants, potentially toxic metals, etc.) can be kept out of the waste stream or removed to an extent that the product is safe for reuse. It is therefore necessary to study the various NBS units and its input and output resource flows derived from the urban activities. Several NBS units in combination with several supporting units (SU) can together form a resource recovery system to help the recovery of above-mentioned elements and mitigate risks associated with contaminants. In that way, the methodology introduced with the concept of NBS can be proved to fulfil the goals previously set out. While biological processes are the foundation for NBS, other units based on chemical and physical principles may be required to effectively "close the loops". The mass and energy balances of SU also need to be studied in detail to comply, when necessary, with the demand on outputs streams quality and reduction of footprint. Within this study, those NBS units including the SU that have been applied as part of a circular system in a local, city environment, are discussed.

In this way, this publication serves as a follow-up to previous contributions of the COST Action Circular City, since it expands on the findings of previous publications. A previous COST Action Circular City publication in particular (Kisser et al., 2020), which provides an ample list of NBS which perform resource recovery activities, is the basis for the NBS and SU selected in this publication. The selective criteria are based on a novel methodology expanded upon in the following chapter. Resource flows (water, nutrients, energy, bioresources) passing through selected NBS and SU are provided, expanding them on the characterization of real-life cases already implemented in cities. The purpose is to provide a detailed guide of the possible resource recovery solutions, mostly technological, alongside any limitations or challenges to be resolved in order to achieve the circularity by implementation of NBS in cities. As a result, we provided a compelling archive for consultation on the merits of these novel solutions as good options to be implemented further in urban areas, in order to guarantee the sustainability of cities within and outside the European Union.

2. Methodology

The present paper applies the definition for NBS-units of Langergraber et al. (2020), viz. "technologies that bring nature into cities and those that are derived from nature, using organisms as principal agents if they enable resource recovery and the restoration of ecosystem services in urban areas".

When building NBS-systems for resource recovery, next to NBS-units mostly described by Langergraber et al. (2021), often physical/chemical SU are needed to enable the production of high concentration products, like precipitates from phosphorus or ammonium salts, or to remove pollutants, like pharmaceuticals, personal care products or pathogens. Based on the paper of Langergraber et al. (2021), a selection of these SU is also discussed in this paper. All selected NBS- and SU are analyzed for potential city input and output streams and systematically presented in Supplementary materials A and B, respectively. Additional NBS units as well as other SU that contribute to resource recovery have been introduced in the present paper.

The criteria for selecting the NBS- and SU, analyzed in the present paper are:

- Relevant for recovery of resources like water, CO_2, nutrients, energy, organics, and metals from city (waste) streams;
- Already applied (TRL >5) as a unit in a local (decentral) circular system (micro- [household], meso- [district] and macro- [city and above]) scales; (Langergraber et al., 2020; Kisser et al., 2020) in the city;
- Applicable in an urban environment.

3. Results

3.1. Liquid incoming streams

3.1.1. Treatment wetlands

Working principle

Treatment wetlands (TWs) (also called constructed wetlands) comprise a series of engineered systems designed and constructed to mimic natural processes found in natural wetlands involving vegetation, soils, or gravel and their associated microbial communities to provide treatment for various wastewater streams. TWs are divided into two main hydrologic categories: (a) open-water surface wetlands, which are shallow sealed basins (one or a sequence) with open water areas planted with floating, submerged, or emergent wetland plants (similar to the appearance of natural marshes); and (b) subsurface flow wetlands, which consist of one or more deeper sealed beds filled with gravel and sand. Water flows below the surface level of the filter bed, either horizontally (horizontal flow or HF wetlands) or vertically (vertical flow or VF wetlands) (Somarakis et al., 2019; Dotro et al., 2017).

Application of subsurface flow wetlands are the most appropriate in cities. TWs can be applied in micro-, meso- and macro scales, which also result in different end users - from individuals, local communities to water utilities. Although the majority of TWs are applied in rural areas to provide on-site or decentralized wastewater treatment, their application in urban settings is gaining attention (e.g., TW in Orhei for 20,000 PE as the main wastewater treatment plant of a city; Masi et al., 2017). However, since cities face very limited space and TWs require a large area, which is their biggest constraint, new types of TWs are being developed, such as rooftop wetlands or vertically oriented systems. Vertically oriented systems which treat wastewater are also called (intensive) green walls and have been investigated mainly for greywater treatment (e.g., Masi et al., 2016; Boano et al., 2019; Prodanovic et al., 2019). Implementations often aim for treated water reuse in the form of onsite fertigation or toilet flushing, for example in the stepwise aligned indoor/outdoor vertECO© system installed at a touristic resort in coastal Lloret de Mar, Spain (Zraunig et al., 2019). Current setups at TRL7 prove the applicability of green wall systems even for the liquid-phase of household wastewater (HOUSEFUL project; EU Grant Agreement ID: 776708; https://cordis.europa.eu/project/id/776708).

In and outputs

In terms of incoming wastewater flows, most of TWs receive primary treated domestic wastewater. Primary treatment includes various sedimentation units (SU 7). Primary treated domestic wastewater contains 30-40% initial suspended solids and 60-75% initial BOD_5. TWs can also receive secondary treated domestic wastewater, which has low organic and suspended solids content and high nutrient content, and act as a tertiary treatment step. In addition, TWs can also be used for the final treatment of tertiary treated water. The content of components in secondary and tertiary treated water depends on the national regulatory requirements for secondary and tertiary treatment in the country where the system is used. In addition, TWs can be used to treat greywater, industrial wastewater and rainwater. Greywater has the following characteristics: COD 200-700, BOD_5 100-400, TN 8-30, TP 2-7 mg L^{-1} (Sperling, 2007; Henze and Comeau, 2008). As mentioned above, most green wall TWs built and investigated so far treat greywater. However, the treatment of the liquid phase of household blackwater has been tested successfully in the ongoing HOUSEFUL project (EU Grant Agreement ID: 776708; https://cordis.europa.eu/project/id/776708).

The key output of the TWs is secondary, tertiary, and finally polished treated water with the characteristics according to the respective national legislation and the solids retained in the primary treatment in the form of the primary sludge. A special type of VF TWs - French reed bed - is designed to receive raw domestic wastewaters. In this case, the solids are not removed in a primary settler, but accumulate on the top layer of a vertical filter bed. The accumulated partially mineralized and dewatered sludge is removed every 10 –15 years (Molle et al., 2005).

By planting herbaceous or woody plants, TWs provide plant biomass. The biomass production of *Phragmites australis*, the most common plant used in TWs, is 19 ± 13 t ha^{-1} y^{-1} when used for secondary treatment of domestic wastewater (Avellan and Gremillion, 2019). A special type of TW, so-called evapotranspirative systems, where short-rotation willows are planted in the treatment beds, can produce more biomass as reeds, e.g. 22-26 t wood chips ha^{-1} y^{-1} (Lachapelle et al., 2019; Istenič and Božič, 2021).

Connected units

Regarding liquid in/outputs, TWs can be connected to phosphorus precipitation SU because phosphorus could be recovered or removed. For the further removal of specific pollutants, TWs can be combined with activated carbon units, advanced oxidation processes, and membranes. The reclaimed water can be used for irrigation or fertigation of street trees and urban parks (NBS 39, 40, 41), urban agriculture (NBS 47, 49, 51 (Canet-Martí et al., 2021) or any other unit to cover water needs.

Regarding solid in/outputs, TWs are usually connected to solid liquid separation (settling tank) as a SU. The sludge can be further treated in an anaerobic digestor to produce biogas and in sludge drying bed to produce soil amendment. The biomass can be composted to produce fertilizers or a compost matrix; the woody biomass can be used for river revitalization elements (NBS 28) or for an energy production or as source of lignocellulose for production of composite materials.

Case studies and literature

Within the city TWs are recently applied mainly for greywater treatment in sustainable housing estates or public institutions. The treated water is used for groundwater recharge (Lübeck, Germany), toilet flushing (Hannover, Germany) or irrigation of vegetable gardens (Lima, Peru - https://www.susana.org/_resources/documents/default/2-70-en-susana-cs-peru-lima-sanchristoferus-2009.pdf). In the latter case study, a separate TW is also used to treat liquid fraction of blackwater and the treated water is used for irrigation of lawns, fruit trees and flowers. The listed examples apply to micro and meso scale and are also presented in Table 1.

Observed co-benefits and limitations

The co-benefits of TWs arise mainly from the presence of plants, which contribute to the mitigation of heat islands via evapotranspiration, provide habitat for insects, birds, and other wildlife, thus increasing biodiversity, sequestering carbon in their biomass and enabling its reuse. Plants in TWs also play an important role in the aesthetic appearance of the plant and its integration into the landscape (Ghermandi and Fichtman, 2015). TWs can also be used for mitigation and treatment of combined sewer overflow thus reducing floods (Rizzo et al., 2018). An additional benefit in the case of green walls is the added insulation effect for buildings when placed on the exterior walls as well as a potential thermal regulation effect if systems are operated indoors (Assimakopoulos et al., 2020; Boano et al., 2020; Estelrich et al., 2021).

Contribution of this NBS unit to the mitigation of urban circularity challenges

TW are addressing numerous urban challenges: via wastewater, they provide reclaimed water for irrigation or fertigation thus contributing to restoration and maintenance of urban water cycle (Masi et al., 2018). Additionally, the produced plant biomass that can be composted, contributing to nutrient recovery and reuse, or used for energy production (Masi et al., 2018; Istenič and Božič, 2021). TWs plant biomass can be used as construction material in ecologically oriented construction as raw material for roofs but also different materials can be produced from it such as composite panels or insulation material (Maddison et al., 2009; Bajwa et al., 2015; Krus et al., 2015).

3.1.2. Photobioreactors

Working principle

Photobioreactors (PBRs) for nutrient recovery from wastewater are autotrophic wastewater treatment systems housing organisms such as microalgae, which tolerate high loads of wastewater, enable pathogen inhibition, carbon dioxide (CO_2) capture, oxygenation as well as valuable biomass production (Cai et al., 2013; Žitnik et al., 2019). Mainly two types of PBRs can be utilized as NBS units, open raceway ponds or closed panel systems (tubular/flat). Open raceway ponds are designed to be cost-effective, shallow water depth units with paddlewheels or blower pumps for aeration. Natural sunlight is usually preferred for illumination, however, greenhouse settings supplemented with artificial light (LED or similar) are common. Closed systems are generally more expensive, yet controlled units with CO_2 supplements and continuous monitoring of system parameters such as artificial light illumination, dissolved oxygen, temperature, etc. In PBRs, microalgae and aerobic bacteria can have symbiotic interactions with the exchange of different organic and inorganic compounds, such as minerals, vitamins, and gases. Green microalgae are primarily autotrophs; however, some species can grow as heterotrophs in the absence of light and thus compete with bacteria for organic sources or carbon. Microalgae growth depends on temperature, concentration of mineral nutrients, pH, intensity, and duration of illumination (Barsanti and Gualtieri, 2014; Ramanan et al., 2016). Thus, domestic wastewaters usually lack the carbon required to remove all nitrogen by assimilation into algal biomass, indicated by elevated daytime pond water pH, resulting from inorganic carbon assimilation causing a shift in the carbonate system equilibrium and release of hydroxide ions which can increase pond water pH to >10. However, optimum range of pH and dissolved organic carbon can be regulated by injection of CO_2, enhancing algal production, promoting aggregation and bio-flocculation of algae with bacterial flocs to further enhance algal settling (Park and Craggs, 2010) and nitrogen removal by providing the necessary carbon to stimulate algal growth and reduce pH (Craggs et al., 2012). In PBRs optimal conditions for microalgae growth should be maintained to achieve maximum efficiency of the system including vital algae inoculum, sufficient light availability for algae growth, hydraulic retention times (up to 20 days) and surface area needed for algae ponds (20 g dry weight m^{-2} d^{-1}), while avoiding contamination by fungi and zooplankton (Passos et al., 2015; Gouveia et al., 2016; Segovia Bifarini et al., 2020).

In and outputs

In terms of inputs, PBRs can receive primary, secondary treated wastewater, digested effluent of municipal wastewater and anaerobically treated blackwater and urine (Tuantet et al., 2014; Vasconcelos Fernandes et al., 2015; Sutherland et al., 2020), digestate from a biogas plant, and different sources of CO_2 from e.g., tailpipe CO_2 from cars/buses/trucks, or combusted CH_4 gas if located in the city. PBRs can also treat the effluent of tertiary treated water. However, very dark color of the wastewater can limit light availability for algae growth, and it should be considered regarding inputs. The quality of the listed influents depends on requirements of national legislations. Under optimal operational condition, the main outputs are treated municipal wastewater, grey/blackwater, urine, treated digestate and efficiently harvested algae or algae-bacteria biomass which can be used as an organic fertilizer in agriculture, biofuels, biopolymers, animal feed, bio-stimulants and substances like pigments for cosmetic and pharmaceutical industries (Žitnik et al., 2019). Algae biomass contains micro- and macronutrients, especially N, P, and K, and might be considered as an organic slow-release fertilizer (Coppens et al., 2016)**.** Sludge from primary settler can be anaerobically digested for energy recovery or biogas production.

Connected units

Anaerobic treatment can be connected to produce an input stream for the PBR containing mainly nutrients and non-biodegradable chemical oxygen demand (COD). PBRs effluent can be connected to a primary settler of raw wastewater to remove organic solids as a pre-treatment unit and to harvesting unit to separate algae or algae-bacteria biomass from liquid, followed by additional effluent polishing if required by the legislation or end-users by a) UV disinfection, b) sand filter for final solids removal, c) activated carbon unit, d) advanced oxidation processes, and c) membrane filter for efficient removal of specific pollutants or to provide a high-quality effluent, suitable for many re-use applications. After harvesting, the biomass can be additionally treated to meet specific requirements in a maturation pond for further solar-UV disinfection, used as storage before discharge or subsequent re-use (Craggs et al., 2021). The biomass, if not used as fertilizer or in industrial use, can be further treated in an anaerobic digestor to produce biogas and in sludge drying bed to produce a soil amendment. The final effluent from PBRs can be used for irrigation of street trees and urban parks, urban agriculture, while algae or algae-bacteria biomass can be used in urban agriculture. Both products can be used in any other NBS unit to cover water and fertilizing needs.

Case studies and literature

PBRs are applied on micro-, meso-, and macro scales with different end users; communities to water utilities. However, due to the high surface size requirements of PBRs (e.g. 0.3 $m^3 m^{-2}$), their application in the city is rare. However, Sutherland et al. (2020) report that the optimum size for maximum productivity is considerably smaller than the current full-scale systems, suggesting that a combination of mixing frequency and higher photosynthetic potential under low light conditions were the main drivers of enhanced productivity. This has implications for commercial scale systems also located in the city, with respect to capital and operational costs. (e.g., comparison between different PBRs scales of 5 m^2, 330 m^2, 1 ha; Sutherland et al., 2020). It was reported that a full-scale pilot project SolarLeaf façade was installed on the BIQ house in Hamburg in 2013 (https://www.archdaily.com/339451/worlds-first-algae-bioreactor-facade-nears-complet), consisting of bioreactors to form a secondary façade and provides around 1/3 of the total heat demand of the 15 residential units in the BIQ house.

Observed co-benefits and limitations

Harvested algal biomass has several multi-valorization pathways, such as bio-stimulants and fertilizer for soil amendment, feed for different animal groups, and bio-composites for construction purposes. There are also several co-benefits while treating wastewaters like microplastic, contaminants of emerging concern (CEC), and pathogens removal. As a matter of fact, biodegradation and photodegradation are the most important removal pathways for CECs achieving up to 90% removal efficiency (Matamoros et al., 2015). However, several risks can influence the outputs. Among them, fungi and zooplanktons contamination, inappropriate pH range, inefficient CO_2 injection and inefficient harvesting, seasonal algae die-off, and self-shading are the most usual ones.

Contribution of this NBS unit to the mitigation of urban circularity challenges

Photobioreactors allow sustainable biomass (algae or algae-bacteria) generation while upcycling nutrients readily available in urban wastewater. As a result, urban circularity dual benefit from avoided emissions for making new fertilizer or feed compounds, while achieving treated wastewater with reduced costs. When photobioreactors are operated in autotrophic mode, significant amounts of CO_2 capture can be achieved helping to reduce urban emissions generated as industrial flue gas or from transportation related activities.

3.1.3. Anaerobic treatment

Working principle

Anaerobic digestion combines treatment of contaminated waste streams with the production of energy and nutrients in a recoverable form. In oxygen absence, different groups of microorganisms (the biomass or sludge) cooperate to transform complex organic matter in four sequential steps to methane and CO_2 (biogas). In the process, the complex organic matter is firstly hydrolyzed and subsequently fermented (acidogenesis and acetogenesis) to substrates (acetate, H_2/CO_2, C1 compounds) which can be converted to methane (methanogenesis). In the process, nutrients bound to the organic matter are released in their water-soluble forms (ammonium, phosphate), which are not further converted under the conditions applied. These nutrients are available for recovery and reuse as, for example, fertilizers (provided that the salts do not precipitate in the sludge). For soluble organic matter like glucose, amino-acids and volatile fatty acids, the conversion to biogas takes place in a similar way, starting with (depending on the nature of the organic matter) acido- or acetogenesis (Weinrich & Nelles, 2021).

Usually, two different systems are distinguished for continuous anaerobic treatment: low rate systems without biomass retention, which are completely mixed and applied for input flows that have high suspended solid and COD concentrations (> 50 g/L), and high-rate systems with biomass retention that are fed with input streams with lower COD concentrations.

In and outputs

A large variety of input streams can be treated anaerobically, if certain conditions are met. Organic matter should be biodegradable for an important part and more or less free of inhibitory compounds. Anaerobic systems are currently operating for a variety of inputs ranging from domestic and industrial wastewaters, agro-industrial plant residues, manure, sewage sludge and (fractions of municipal) solid waste. The application scale is also highly variable; large scale systems are operating for industrial and municipal wastewater treatment. UASB is one of the suitable processes for both carbon removal and energy recovery from domestic wastewater streams (Owusu-Agyeman et al., 2019, 2021). In the past decades, smaller systems have been installed for black (toilet) water (BW) treatment as a result of the implementation of source-separated sanitation concepts (Kisser et al., 2020). Production of volatile fatty acids (VFA) from, for example, primary sludge (Atasoy et al., 2018; Owusu-Agyeman, 2020) and also polyhydroxyalkonates production (Perez-Zabaleta et al., 2021), can be an alternative to biogas production.

Connected units

Conventionally collected, low concentrated, domestic wastewater can be treated anaerobically, when tropical conditions are prevailing (Seghezzo et al., 1998). For low temperature climate, low flush toilets, like vacuum toilets, need to be installed, in combination with separation of the greywater from the blackwater, to provide a concentrated black water suited as an influent for a heated (mesophilic) anaerobic treatment system (Zeeman, 2012). Regardless of the end-product, anaerobic treatment usually requires post treatment. In general, effluent COD concentrations are too high to allow for direct use of the effluent, for example as nutrient rich solution for fertilization of continuous (all year round) crop systems. Supporting units like struvite precipitation for P recovery, ammonia stripping/absorption, for nitrogen recovery and aerobic treatment can be included after the anaerobic treatment. Moreover, pathogens can be present (depending on the input substrate) in high concentrations. Post treatment for organic micropollutants and pathogens removal is needed to ensure high end-product quality. Gas treatment needs to be installed (for desulfurization) and odor control needs to be ensured. Different post treatment, supporting, units are presented in Supplementary materials B.

Literature case studies

Various NBS systems on a micro-, meso- and macro scale (Table 1, based on Kisser et al., 2020) have been implemented in the city for the recovery of resources (N, P, energy, organics, water) from household waste (water) streams in which the anaerobic mesophilic NBS unit is the core technology of the system. Recently, on a scale of ca. 2000 people (meso scale), apartment buildings in Helsingborg (H+ project) were equipped with source separated sanitation and mesophilic anaerobic treatment of black water and (in a separate unit) food waste. Energy and organic fertilizer are produced during anaerobic treatment while struvite and ammonium-sulfate are recovered from the anaerobic effluents via respectively a struvite precipitation and a stripping/absorption unit (Table 1). In Sneek, the housing project at the Lemmerweg (Zeeman et al., 2008) was recently upgraded with ultra-low-flush vacuum toilets connected to a thermophilic anaerobic system for hygienized fertilizer recovery from blackwater.

In Stockholm, primary settled wastewater from Henriksdal WWTP was pre-treated in UASB reactors followed by partial nitrification/anammox for mainstream nitrogen removal (Malovanyy et al., 2015).

Observed co-benefits and limitations

Energy is produced in the form of biogas, and it can be applied to increase reactor temperature, minimizing external energy demand. Nutrients are retained in the effluent and can be recovered for use as a fertilizer in agriculture either as is (directly) or after application of a recovery supporting unit (e.g. struvite SU 3, and ammonium after stripping SU 4 in Supplementary materials B). Sludge can be reused in agriculture after a disinfection step. Streams with a low COD concentration and low temperature (for example conventionally collected domestic sewage) produce too low amounts of biogas to increase the process temperature. Therefore, large reactor volumes are needed. Source separation of blackwater using low flush toilets (e.g. vacuum) can tackle this issue.

Contribution of this NBS unit to the mitigation of urban circularity challenges

Our food is grown in agriculture with nutrients or comes from animals fed with agricultural products and these nutrients are excreted after consumption via urine and faeces or end partly in kitchen waste. Recovery of nutrients, through the application of anaerobic treatment of domestic waste and wastewater streams, followed by the above-mentioned NBS units and subsequent use in agriculture contributes to a circular economy. Since anaerobic treatment is used with the aim of reaching energy neutrality, no additional energy is required and in some cases an excess of energy is produced.

3.1.4. Aerobic treatment

Working principle

Aerobic treatment is based on the oxidation of organic material and nutrients (for example nitrogen) by micro-organisms. Carbon is oxidized to CO_2, and biomass (sludge) and nutrients are removed via a combination of denitrification/nitrification for nitrogen and via chemical or biological P removal. In some cases, the process is limited to mainly nitrification as it is in the VUNA process for recovery of nutrients from human urine (Fumasoli et al., 2016).

The process can be performed in several types of aerated reactors. Often it is combined with a settler or a membrane process (SU 7 or SU 8 in Supplementary materials B) to ensure high effluent quality. Due to the recirculation of effluents from the membrane and biological processes, this combination is sometimes described as one technology.

In and outputs

Aerobic treatment is most suitable for diluted wastewater streams, for instance separately collected domestic greywater, the effluent from blackwater treatment or a combination of the two can be used as input streams. The main output of the process is the treated water. This water has high quality and with further polishing can be safely reused. Furthermore, sludge is produced.

Connected units

The incoming stream is most often first treated or collected in a settling tank. The aerobic treatment is sufficient to reach wastewater effluent standards. However, the aerated tank can further be connected to a membrane filter or micropollutant removal system (e.g. UV) (SU 5 or SU 8 in Supplementary materials B) for high effluent quality to increase possibilities for reuse. Furthermore, because greywater can have high temperatures, it has great potential for heat recovery, therefore heat exchangers can be integrated in the system.

Literature case studies

Various aerobic treatment systems on mesoscale have been implemented in cities for the recovery of water from diluted household wastewater streams (Table 1). In Helsingborg (H+ project) a membrane bioreactor is used to treat domestic greywater and in Gent a similar system has been implemented to treat a combination of domestic greywaters and effluents from blackwater treatment (Run4Life EU project – Recovery and utilization of nutrients 4 low impact fertilizer - https://cordis.europa.eu/project/id/730285, n.d.). The effluent produced in Gent will be reused in a soap factory (Nereus Project - New energy and resources from urban sanitation - https://www.nereus-project.eu/, n.d.). In Berlin, a moving biofilm bed reactor is applied in combination with heat recovery and UV disinfection to reuse heat and water for toilet flushing (Nolde E., 2014). In the neighborhood Klosterenga in Oslo, the greywater of an apartment building is treated by an aerobic bioreactor in combination with a porous media filter and a subsurface TW. The effluent is used in a local garden with a playground for kids (Peter, D.J., n.d.). In the Sneek, the Netherlands, an aerobic treatment in combination with nanofiltration was tested for 6 months and proved to reach high effluent quality as well (Sanimonitor, n.d.). These case studies show that in combination with different connecting units, aerobic treatment is well suited for reuse purposes of water in the city.

Furthermore, aerobic treatment can be used for the treatment of separately collected urine. As part of a fully operational urine-separating sanitation system (TRL 7) at EAWAG, Switzerland, two moving bed bioreactors (MBBR) have been in operation for several years (Fumasoli et al., 2016). Regarding the removal of pharmaceuticals from the treated urine, a post-treatment step is necessary, e.g., by powdered activated carbon (PAC) (Özel-Duygan et al., 2021).

Observed co-benefits and limitations

The benefits of using aerobic treatment are, the high effluent quality and therefore possibilities for reuse of wastewater, the compactness of the reactors, and due to the removal of most of the organic substances re-growth of micro-organisms and odor problems are less likely to occur (Li et al., 2009). Furthermore, aerobic treatment is mostly suitable for the treatment of greywater. By separately collecting greywater from residential buildings a high temperature stream is created, which makes aerobic treatment ideal for the combination with heat recovery.

Constraints of aerobic treatment are the usually high sludge production and often the need for an external C source dosing for denitrification. When treating the effluent of a blackwater treatment, this last constraint can be solved by applying a nitritation/anammox on the blackwater effluent before it enters the aerobic treatment. Because the nitritation/anammox can remove 70-90% of the blackwater effluent stream (Vlaeminck et al., 2009; de Graaf et al., 2010) it reduces the need for an external C source in wastewater treatment. Further constraints are mainly found in financial, legal, social issues; high costs for implementation of wastewater separation in existing buildings, legal obligation of water quality for reuse, and the willingness of end-users to use recycled water. Another issue that can arise is the pharmaceutical content. In Sneek, it was seen that aerobic greywater treatment was not sufficient to remove certain pharmaceuticals (Bukovski et al., 2015). This is an area for further consideration.

Contribution of this NBS unit to the mitigation of urban circularity challenges

Aerobic treatment (in combination with connecting units) provides the possibility to reuse diluted wastewater streams. This allows for the circular use of water instead of linear use. Moreover, it can supply a constant flow (all year round) of clean water which can be beneficial in reuse purposes in, for instance, industries. Furthermore, the circular economy aims at minimizing input of energy. As aerobic treatment is ideal for use in combination with heat recovery from wastewater, it decreases the need for energy consumption for heat production in residential areas.

3.2. Solid incoming streams

3.2.1. Composting and vermicomposting

Composting comprises (principally) aerobic processes for the oxidation of organic matter or biosolids in (mainly) end product amenable to resource recovery with a minimum capital investment and relatively small operating commitment, with the aim to stabilize the organic matter in the product (compost), reduce the number of pathogens and to obtain a relatively dry product (de Bertoldi et al., 1983; Epstein, 2017).

At the beginning of the process, mesophilic bacteria naturally present in the input waste or inoculated decompose the readily biodegradable fraction of the organic matter. During these initial stages, the temperature of the compost keeps increasing also until 60°C (de Bertoldi et al., 1983; Epstein, 2017). Thereafter both thermophilic bacteria and fungi take over degradation of the remaining biodegradable matter. The high temperature ensures a hygienization of the compost product (de Bertoldi et al., 1983). After most of the readily biodegradable matter has been modified, during the cooling stage of the process, mesophilic bacteria but also other higher organisms continue the breakdown of the organic matter to finally reach a maturation phase in which the compost is completely stabilized. The process as a whole can take several weeks to months (PWGSC, 2013; Epstein, 2017) and high-quality compost is related to its stability and nutrients content. Vermicomposting is also oxidation of organic matter resulting in smaller volumes, but in that process worms (*e.g., Eisenia fetida, Perionyx excavatus, P. sansibaricus, E. andrei, Eudrilus eugeniae*) are the main actors (alongside normal microbial biomass; Lazcano et al., 2008). As worms, in general, are not heat tolerant, vermicomposting usually does not include a thermophilic phase (Loehr et al., 1985).

In and outputs

Composting can be a simple process on small-scale (home composting) to a controlled large-scale operation. For home-composting usually, a bin (or heap) is filled up with fresh material and compost is used as the starter. For larger scale, confined boxes or tanks and tunnels could be used.

Typical waste streams to be composted are vegetable materials, crop residues, dry (no water or urine) feces, biological sludge from wastewater treatment plants, green cuts, with a dry matter content higher than 40% and a C/N ratio ranging from 25-30 (Lohri et al., 2017). Aeration is done manually (e.g. by waste overturning) during the process and the operator manages the input by ideally alternating the addition of readily biodegradable material with more resistant lignocellulosic inputs. The temperature of the bin/heap is not controlled (but can be steered by addition of readily biodegradable organic matter) nor the humidity.

In the case of vermicomposting, worms need to be added. Temperature needs to be controlled in the mesophilic temperature range. Vermicomposting relies on the worms to mix/aerate and fragment the input. The worms are light-sensitive, so conditions should be controlled.

Larger scale composting facilities decrease the size of the input material to (usually) < 5 cm, and the input material is mixed with an inoculum (compost), and bulking material with a high C/N ratio to increase the passive aeration or facilitate the active one. Humidity is controlled in these systems. Off gas air is usually treated in biofilters. The composition of the output material depends largely on the quality of the input materials but largely 30-60% of the input carbon is oxidized to CO_2 during composting (Harder et al., 2019).

Case studies and literature case studies

Thousands of municipalities in Italy apply the so-called "kerbside collection programs", focusing on food waste collection. This approach is based on small volume kitchen caddies fitted with biodegradable bags (i.e., compostable bioplastic or paper liners); collection is done at the kerbside (or door-to-door collection) and adopting convenient frequencies aimed at enhancing citizen's participation in composting.

This strategy is also used in absence of the plant dedicated to the treatment of organic waste. An example could be the Province of Lecce that doesn't have a dedicated plant and this has stimulated the municipalities to look for strategies and solutions in order to reduce the costs of waste disposal and enhance the enhancement of the organic fraction. Therefore, the Municipal Administrations have equipped themselves with the community compost, which allow to autonomously treat part of the organic waste produced on its territory and to reduce both the production of waste and the costs of transport and conferment by testing a sustainable management system for community composters (Community Composters, 2021).

In other EU countries, home composting is an almost normal practice. For example, 48% of people in Slovenia were reported to have home composting systems (Žitnik and Vidic, 2016). The home process is also used beside urban composting plant (Spain; Mato et al., 2019). A community composting project in the city of Bratislava, Slovakia, demonstrated the importance of cooperation among the various stakeholders and citizens interested in composting their own bio-waste, and resulted in a reduction in the amount of bio-waste in mixed municipal waste.

Malpils Biotechnology Centre (in Latvia) is involved in biowaste treatment using the method of vermicomposting and production of organic fertilizer from it. The main aim is to study the problem of how to process biowaste in all its complexity in order to produce a high-quality product from different types of biowaste (e.g. sewage sludge, manure, leaves) by covering the whole treatment cycle, from the collection of the biowaste to the final treatment and selling of the fertilizer. As the method of vermicomposting is not widely used around the Baltic sea, further studies of the technology should be carried out to find the most efficient ways to adapt it to Latvia's waste management needs. The pilot project has elaborated the technology for preparation of composts predicted for feeding the earth worms used as improvement method for compost quality (Malpils Biotechnology Centre, 2021).

Observed co-benefit and limitations

Composting inevitably generates some emissions, such as gases and bioaerosols. The gases include CO_2, CH_4, N_2O, sulphur compounds and many other volatile organic compounds (VOCs) that can be also odorous (Dhamodharan et al., 2019) and have to be considered in the neighbor urban agglomerate (Colón et al., 2012). In composting facilities, there is a huge bioaerosol production but, currently, there is no evidence of the toxicity of these bioaerosols, thus the risk to nearby residents cannot be quantified (Robertson et al., 2019).

Composting may also be a source of microplastics in the environment. Gui et al. (2021) found that "rural domestic waste compost was a significant source of microplastics in soils, and the microplastics in compost products were closely related to the quantity and type of plastic waste present in rural domestic waste".

Composting and vermicomposting has various effects on heavy metal concentrations in the end-product. Some papers demonstrate an increase in metal (Cd, Cu, Pb, Zn) concentrations, others show decrease (Hartenstein et al., 1980; Leita and De Nobili, 1991; Shahmansouri et al., 2005; Mohee and Soobhany, 2014). Composting also tends to stabilize metals (Paré et al., 1999) with redistribution from relatively labile to more immobilized states. For this reason, all compost should go through quality control before use. Finally, issues related to leachate infiltration and runoff must be considered since they can be emitted during the process if not well managed (Colón et al., 2012).

Contribution of this NBS unit to the mitigation of urban circularity challenges

Compost application is a way to improve soil health by enhancing its organic matter (critical for most soil functions like soil structure, water purification and regulation, carbon sequestration and regulation, biodiversity and nutrient cycling), microbial diversity as well as soil fertility and soil health even in cities. Moreover, it is also a way to prevent waste of raw materials and to reuse them. The compost produced by households or small communities can be used at the local level. In this way, citizens may benefit from a good-quality fertilizer and soil improver, such as compost/vermicompost, for use in their gardens or vegetable plots avoiding disposal. This is a typical example of closing loops locally. However, home composting requires people to have some knowledge of good composting practice in order to avoid unnecessary environmental impacts and to ensure good-quality compost. Therefore, the success of home and community composting depends on the quality of waste separation and citizens' management of the composting process (EEA, 2020) and to teach how to compost waste materials (Fertile Auro, 2019). The challenge in cities is to contribute using it as soil improver and fertilizer and the acceptability in producing it in urban areas because of its smell and low handleability.

3.2.2. Decentralized solid waste anaerobic treatment in urban areas

Working principle

Solid waste anaerobic digestion (SWAD) is a biological process that breaks down residual organic material (OM) via microorganisms in the absence of oxygen. The AD of organic material basically follows hydrolysis, acidogenesis, acetogenesis and methanogenesis biochemical steps. Volatile fatty acids (VFA) formed after the acidogenesis step are intermediates in the process of conversion of biodegradable OM to methane. By inhibition of the last steps (i.e., acetogenesis and methanogenesis) in the anaerobic conversion, VFA can accumulate in the system and as such be harvested as an end product. SWAD produces biogas, a methane-rich gas that can be used as a fuel, and digestate that is a source of nutrients that can be used as a fertilizer. Biogas can be converted to heat and electricity through combined heat power (CHP) engines, while the digestate can be further processed to separate water from the solid containing nutrients fraction using techniques such as a settling tank or electro-coagulation. The use of AD on a microscale is very much implemented in low and middle countries, however nowadays one sees a trend regarding its application in developed countries urban areas (e.g. A DECentralIzed management Scheme for Innovative Valorization of urban biowastE (DECISIVE) H2020 EU project http://www.decisive2020.eu/ ; https://cordis.europa.eu/project/id/689229).

In and outputs

Organic waste represents one of the largest fractions of the municipal waste mass: from 14% to 47% in the European countries; and more than 60% in developing countries.

Urban biowaste such as food waste, the organic fraction of the municipal solid waste and co-substrate (lignocellulosic biomass: green waste from private gardens, green waste from public areas, paper towel from mass and commercial catering,…) can be used as feedstock. In some cases, urban waste is mixed with blackwater in order to generate a slurry (Bautista Angeli et al., 2018). Regarding the outputs, two types of streams are generated, the digestate that needs to be further processed to separate the liquid from the solid fractions and the biogas (mixture of methane and CO_2 with traces of impurities such as hydrogen sulfide).

Connected units

An efficient collection, storage and pre-treatment network is required to supply a constant quantity of organic waste with the best quality to the AD process. Therefore, after collection the organic waste needs to be stored and pre-treated in order to improve their digestibility while minimizing potential odorous nuisances (Bautista Angeli et al., 2018). The management of the output streams involves the post-treatment of digestate and biogas. Usually, digestate cannot be used directly in most urban areas and this required the implementation of a solid-liquid separation supporting unit able to generate a liquid stream as well as a solid stream. The liquid fraction could be treated for fertilizer recovery (i.e., struvite precipitation and/or ammonia stripping). In addition to chemical process, TW or classical aerobic treatment, the liquid digestate may be further processed with PBRs and aquaponics (Fuldauer et al., 2018; Weidner and Yang, 2020). Solid digestate is being composted before being used for urban applications (Guilayn et al., 2020; Weidner and Yang, 2020). For the valorization of biogas, the most common application is the production of heat and electricity by a CHP unit that usually requires to upgrade the quality of the biogas mostly by using a H_2S filter.

Literature case studies

Over the last decade, there have been several aiming at moving from goods importation and extra-urban waste management, to a more urban network allowing circular local and decentralized valorization of biowaste enabling energy and bioproducts production for local uses (e.g. DECISIVE H2020 EU project https://cordis.europa.eu/project/id/689229). While waiting for the outcomes of this later project, several recent publications have reported on the application of decentralized anaerobic digestion of urban organic solid waste at pilot scale (see Angeli et al., 2018 for an overview and Nguyen et al., 2021, Walker et al., 2017; Gonzalez et al., 2020 for more recent pilot-scale studies). For instance, Walker et al. (2017) reported the implementation of micro-scale AD fed on food and catering waste in London (UK). The pilot system was a 2 m^3 single stage digester containing an automated mechanical mixer and heated by an internal water heat exchanger was operated with the necessary input and output process units allowing to store/feed (average OLR of 1.6 kg $VS \cdot m^{-3} \cdot d^{-1}$) and manage safely the output streams, respectively. The biogas plant monitored over 319 days could process 4574 kg of food waste while producing 1008 m^3 of biogas at average *60.6% methane.* Nguyen et al. (2021) have operated a two-stage anaerobic digestion system in Ho Chi Minh city (Vietnam) which include a feed tank (0.4 m^3), a hydrolysis reactor (1.2 m^3) and a methanogenic reactor (4.0 m^3). The reactor was fed with biowaste diverted from municipal solid waste collected from households and restaurants with Organic Loading Rate ranging from 2.5 to 3.8 kg VS m^{-3} d^{-1}. The highest biogas yield of 263 ± 64 $L \cdot kg^{-1}$ t COD removed obtained at OLR of 2.5 kg $VS \cdot m^{-3} \cdot d^{-1}$. It is expected that a full scale 2S-AD plant with capacity of 5200 tons day^{-1} of biowaste collected currently from municipal solid waste in Ho Chi Minh city may create daily electricity of 552 MWh, thermal energy of 630 MWh, and recovery of 16.1 tons of NH_4^+-N, 11.4 tons of organic-N, and 2.1 tons of TP as both organic liquid and solid fertilizers.

Observed co-benefits and limitations

A pre-digester tank to store the feedstock collected and feed the AD is required to buffer the irregular collected volume of biowaste, however the storage duration that may affect AD performance and odor should be controlled (Degueurce et al., 2020). Gonzalez et al. (2020) reported that temperature increase of the feed to process conditions require a significant amount of thermal energy which strongly affects the efficiency of the process when operated at low organic load. However, the amount of energy consumed may be limited if the micro-scale AD process is operated in a greenhouse in temperate climate conditions (Walker et al. 2017). With this approach, Walker et al. (2017) reported a net positive energy balance and potential coefficient of overall performance (COP) of 3.16 and 5.55 based on electrical and heat energy inputs and outputs, respectively.

On site heat and electricity production can fully benefit the housing infrastructure localized nearby the micro-scale AD (Bautista Angeli et al., 2021). Walker et al. (2017) reported that the most important contribution of micro-scale AD was the limitation of greenhouse gases emission by the avoidance of on-site fossil fuel use, followed by the diversion of feed waste from landfill and that the plant could result in carbon reduction of 2.95 kg CO_{2eq} kW h^{-1} electricity production.

Contribution of this NBS unit to the mitigation of urban circularity challenges

If the AD of the urban organic materials could be combined with the development of urban agriculture, the biogas can be burned in a combined heat and power unit allowing to comply to the heat demand of greenhouses while the digestate separated in liquid and solid fractions could be valorized. The liquid fraction being available for hydroponic growing and the solid fraction being amended on soils after further treatment (Weidner and Yang, 2020; Fuldauer et al., 2018). All these outputs may potentially mitigate several urban circularity challenges as detailed by Atanasova et al. (2021). However, all stakeholders shall be involved in the project design and implementation for ensuring the success of decentralized urban organic waste treatment and valorization (Angouria-Tsorochidou et al., 2021). Finally, a method to design decentralized and micro-scale anaerobic digestion efficient networks in urban areas is still needed (Thiriet et al., 2020).

3.2.3. Insect farming

Working principle

Instead of composting or vermicomposting, nutrients in organic waste can also be converted through applying insect larvae (Ojha, 2020). There are several types of insects suitable for insect farming e.g. mealworms, black soldier flies (BSFL), houseflies, crickets, waxworms etc. (Cortes Ortiz et al., 2016). To upcycle organic waste with insect larvae, the waste is ground into small particles or converted to a liquid or pasty state. The insects are bred in a nursery where the eggs take a certain time to hatch, for BSFL it takes around four days. The recently hatched larvae (1-5 days old) are put together with the pretreated waste and start to feed on the organic matter. Depending on quantity and quality of the waste, the larvae will need at least 12-16 days to reach full size of around 0.5 cm width and 2.5 cm length. To treat 60 kg of waste, approximately 40.000 BSFL and 1 m^2 of space is needed. The larvae consume 100-125 mg/feed/day (Larouche, 2019). In the last larval stage, they are harvested. The larvae are quite resilient and can withstand changes in the environment, but for a fast waste conversion and high product yield optimal surroundings are of advantage. Optimal conditions are influenced by: the chosen insect, container dimensions, temperature, larval density, humidity, feeding rate, feeding interval, type of feed (Harnden & Toberlin, 2016). The ideal operating conditions for BSFL are temperatures between 24-32 °C, a moisture content of 60 – 90 % and a shady environment (Dortmans et al., 2017, 2021). The eggs or larvae can easily be bread on the production site. The space needed for 1 ton/incoming waste/day are around 50 m^2 for the breeding facility and 100 m^2 for the waste processing spatiality (Dortmans et al., 2017).

In and output

Many insects can grow on a variety of biowaste such as animal manure, human excreta, fruit and vegetable waste, municipal organic solid waste, millings and brewery side streams (da Silvia, 2020; Diener, 2011). Those are therefore all possible input materials, although for the use of the larvae as animal feed or food, the selection is smaller due to regulations. Protein-rich larvae or extracts from those are the main output and can be used for feeding fish in hydroponics, poultry and pets, as a delicacy or food supplement (Sánchez-Muros, 2014; Wang, 2017). The residual biowaste (mixture of unassimilated material and larvae excrement) can be used as fertilizer and soil amendment in urban gardens and farms (Sarpong, 2019) or can also be converted in biogas units. Depending on the type of input sometimes also some liquid fraction is produced (Silva and Hesselberg, 2020; Müller et al., 2017). Low-value waste is thus transformed into high-value products with diverse potential applications.

Connected units

Beforehand, depending on the incoming waste, some pretreatment of the input stream can be required to obtain the ideal composition for the insects (e.g. shredding, separation, moister content adjustments) (Figure 2). Usually, the waste is shredded to a particle size of less than 1 – 2 cm, which can be performed with a simple gadget like a hammer mill. After feeding in the main unit the larvae are separated from the substrate through sieving. This can be done manually on a small scale or with automatically shaking sieves. The obtained larvae need to be further processed before they can be sold, either by drying, mixing them with other ingredients and producing pellets or by extracting proteins and fats with more complicated processes (Dortmans et al., 2017). The residual biowaste can directly be used as fertilizer but also be further treated in an anaerobic digestion for the production of biowaste (Müller et al., 2017).

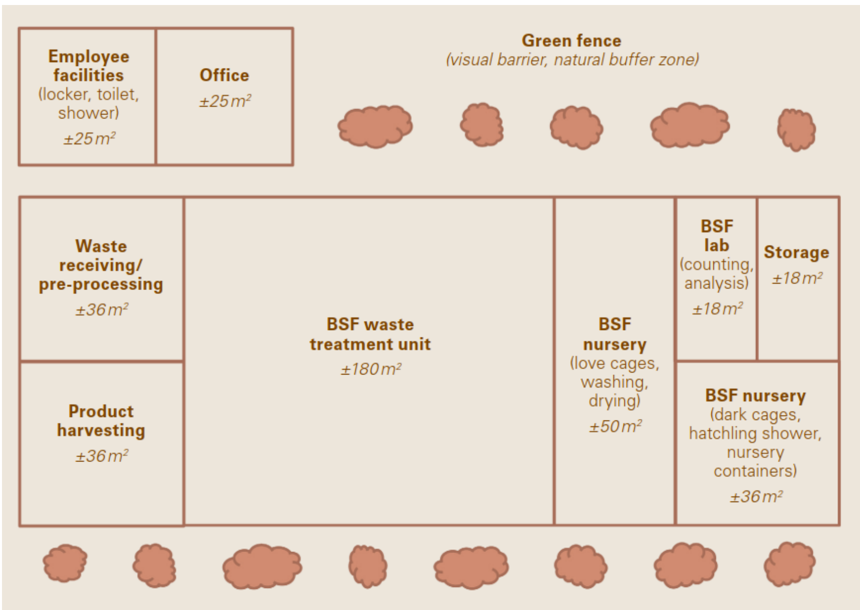

Figure 2. : Draft of a BSFL farm and size estimation for the conversion of 2 tons/biowaste/day (from Dortmans et al., 2017 (CC BY 4.0)).

Literature case studies

In Europe and North America there is more resistance towards insect farming and the legislation is an additional restriction (MacConville, 2020). Due to legislation, there are no cases to be found in Europe of insect farming on domestic waste. On the contrary, in many countries in Asia, Latin America and Africa the use of insects is widely accepted and even already applied, however most examples of insect farming concern larger operations (Bakker, 2020). In the University Catolica de Santa Maria in Peru, a research center has been created to form a basis for the BSFL industry in the country. The company Nasekomo in Sofia, Bulgaria, is producing BSFL on agricultural by-products for feed, oil and fertilizer production on a larger commercial scale (Nasekomo, n.d.). Furthermore, Biobuutz, in Tanzania, has created the Kuku Bonge, which is a home bin for BSFL production on household size. InsectiPro in Kenya is producing BSFL and crickets from organic waste for feed and food purposes on a large scale outside of the city (InsectiPro, n.d.).

Observed Co-benefit and limitations

This process of breeding insects on waste can be applied on a variety of scales, which makes insect farming an NBS unit that is suitable for circular city ambitions around the globe. The build-up of an insect farm does not require advanced material, as they can easily be farmed in containers or boxes and several species can be used. Therefore, it is a simple, inexpensive way to recover nutrients in low- and middle-income countries as well (Dortmans, 2017; Sánchez-Muros, 2014). A further benefit of using insect farming is that it results in higher value products, for instance BSFL consists of 32-58% proteins, 15-39% lipids based on DW (Gold, 2018). The products can also find instant application in other NBS like nearby aquaponic systems as feed for the fish. The only by-product emerging is a compost like substrate that can utilized as soil amendment and fertilizer (Sánchez-Muros, 2014; Wang, 2017). Furthermore, some insects have additional benefits, e.g. BSFL are not bioaccumulating pharmaceuticals and pesticides but instead accelerate the half-life time (Lalander, 2016; Wang, 2017). A reduction in viruses and *Salmonella ssp*. can be observed after fly larvae composting (Lalander, 2014).

Drawbacks are the loss of nitrogen through degassing of ammonia (Lalander, 2014) and for the BSFL in specific the high contents of unsaturated fatty acids (Wang, 2017). While there was no strong bioaccumulation of Zn, Cr, Cu and As in BSFL fed with pig manure, the bioaccumulation factor of Cd was significantly higher. The speciation of the metals was differing in between the pig manure and the residual biomass and pathogens from the pig manure were reduced in the BSFL feces (Wu, 2021; Wang, 2021). The main limiting factors of insect farming lie in the social and legal constraints. In Europe and North America there is still resistance towards the use of insects in food. Though, these perceptions are changing, in a study in Flanders, Belgium, it was found that using insects in animal feed and the foods obtained from animals fed on insects are generally accepted (McConville et al., 2020). Legal issues are more persistent, in most European countries the products from insect farming are only allowed to be fed to fish and/or poultry. Furthermore, insects and are not allowed to be grown on domestic waste, only on verified industrial waste for example potato peels (van Huis, 2020).

Contribution of this NBS unit to the mitigation of urban circularity challenges

Insect farming (in combination with connecting units) provides the possibility to create high value products from organic waste streams. This allows for a truly circular solution for organic waste as the organic waste becomes food again (Weidner and Yang, 2020).

3.2.4. Soil conservation and phytomining

Working principle

Around 340,000 contaminated sites and around 2.5 million potentially contaminated sites are located in the EU (EEA, 2014). Ultramafic and brownfields provide conditions unfavorable for plant growth, primarily due to phytotoxic concentrations of metals, such as Ni, Cr, Co, Cu, Mn, Ni, Pb and Zn, but also due to low nutrient availability, low organic matter content, poor soil structure, absence of topsoil, erosion, surface instability, compaction, and often high acidity. Ultramafic substrates cover large areas in the Balkans (Bani et al., 2021). This region is a potential target for agromining activities and also have the highest diversity in Ni hyperaccumulator plants in Europe and one of the highest globally together with Anatolia in Turkey (Bani et al., 2015a, b, 2021; van der Ent et al., 2015).

Phytomining, or agromining, describes the technique of growing plants to 'mine' metals contained in such soils. This technique comprises a chain of processes covering the improvement of soil quality (phytoremediation) and the incineration of the biomass produced in order to obtain the metals from the ashes of the hyperaccumulator plants, which can be considered as a bio-ore (van der Ent et al., 2015). Thus, metals are extracted by plants and recovered for further use. This non-destructive approach is applied to recover high value metals (e.g. Ni, Co, rare earth elements) from sub-economic (low-grade) ores (Wang et al., 2019). Currently, over 1,000 plant species with the ability to hyperaccumulate metals and metalloids are known, with most of them accumulating either Al, Ni, Mn, or Zn (Reeves et al., 2018), but also Au (Anderson et al., 2005).

Phytoremediation is a technology that uses tolerant plants to clean up soil, water or air contaminated by pollutants (Salt et al., 1998). It can be applied to restore contaminated or degraded soils while producing biomass for industrial use, such as energy, fibre and phytomining. Phytoextraction uses accumulating or hyperaccumulating plants to improve the biological quality of a soil by accumulating trace metals and metalloids from metal-rich soils or substrates (technosols) and transporting them to the harvestable, aboveground shoots (Sheoran et al., 2009; Wang et al., 2020).

In and output

Inputs, as described in Supplementary materials A, include the growing substrate, plants, soil amendment for biostimulation purposes and additional microbial strains for bioaugmentation. Outputs include improved soil, recovered metal bio-ores (metals-enriched biomass of hyperaccumulator plants) and energy from biomass combustion.

The typical edaphic properties of ultramafic soils can severely limit plant growth (e.g. nutrient deficiency, poor soil structure, low organic matter). In areas affected by mining activities, these edaphic properties can be especially severe. Organic residues (composts, manure, biosolids, mulch, wood chips, biochar) are commonly applied to such contaminated soils to improve physical soil properties, water infiltration and water holding capacity, as well as to provide essential micro- and macronutrients for plant growth, and to decrease bulk density.

Connected units

Connected NBS units include treatment wetlands, which could provide reclaimed water and nutrients contained in fertigation water applied to phytomining plots. As mentioned above, compost is a common soil conditioner applied to support plant growth on the unfavourable conditions of metal-enriched soils or substrates.

As described in Supplementary materials B, bioengineering techniques can be applied to support phytomining, in particular for land stabilization to mitigate movement of contaminated soils, as well as to mitigate landslides on slopes, or to stabilize river banks. Sustainable drainage systems can help to optimize soil water and nutrient retention.

Case studies and literature

In Albania, ultramafic soils account for 11% of the land area and are the richest in the number of endemic plant species, including several Ni-hyperaccumulating plants (Bani et al., 2021). Phytomining field plots are operating since 2005 in Pojske, Pogradec (ultramafic), Prenjas serpentine quarries and Elbasan (contaminated by industrial activities). Consequently, cropping systems have been designed. Ni hyperaccumulator *Odontarrhena* *chalcidica* (synonym *Alyssum murale*) cultivated on ultramafic plots in south-east of Albania under organic and mineral fertilization reached biomass production 9.96 t ha^{-1} and the Ni yields 145 kg ha^{-1}. The Ni hyperaccumulator *O. chalcidica* has real potential to become a cash crop (Bani et al., 2021).

Zhang et al. (2014) obtained ammonium nickel sulfate hexahydrate (ANSH) with 99% purity by applying the hyperaccumulator *Alyssum murale* on ultramafic soils in Greece and Albania, drying and incinerating the Ni-rich biomass and a sequence of treatments of the ashes. Koppolu et al. (2004), Zhang et al. (2014) and Houzelot et al. (2017) obtained 5-13% of Ni in the ash from incinerating nickel (Ni) hyperaccumulator plants, significantly higher than the Ni-concentrations in common (primary) ores (3%) (Simonnot et al., 2018)

The LIFE-AGROMINE project (completed in 2021) has provided reference cases on ultramafic agricultural land, ultramafic quarries and technosols based on industrial waste at sites in Greece, Albania, Spain and Austria, demonstrating the full phytomining cycle including the recovery of Ni-rich products and bioenergy (Bani et al., 2021) (Figure 3).

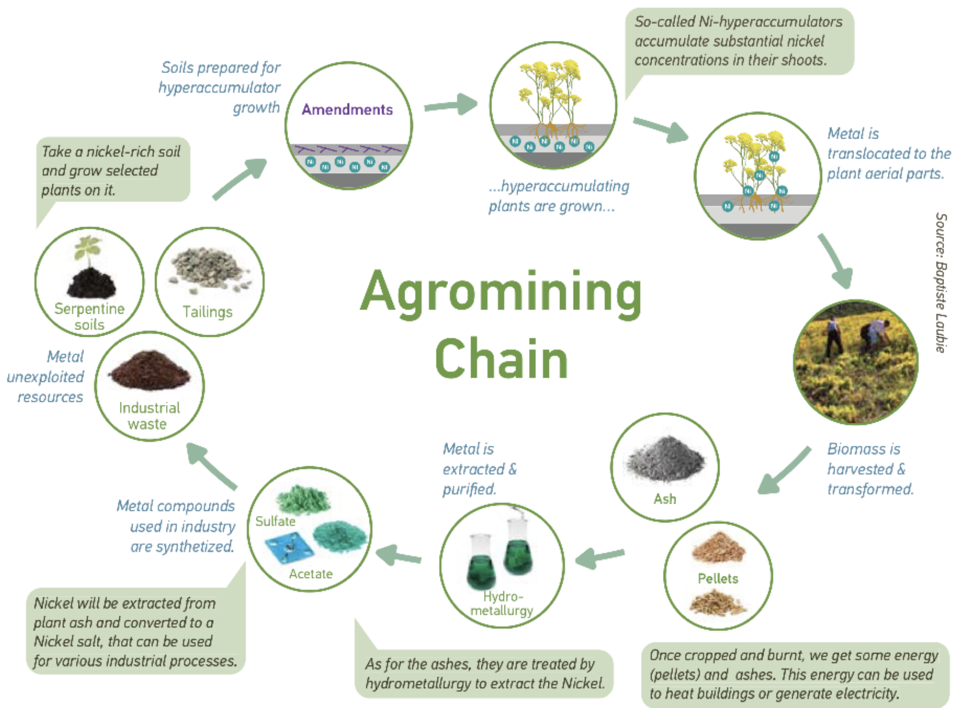

Figure 3. Agromining chain, source: Baptiste Laubie (2019), Layman's Agromine Report published in frame of Life AGROMINE project (https://www.alchemia-nova.net/website2018/wp-content/uploads/2019/08/laymans_agromine_EN-s.pdf).

The principle of phytomining can also be applied to municipal and industrial solid waste streams (Kisser et al., 2015), if the metals are bio-available or made bio-available through appropriate additives (Rosenkranz et al., 2017). Brownfield restoration at the city level can also be combined with phytomining. Also, metals can be leached from the waste body through application of suitable microorganisms (Dodson et al., 2015). The further refining and recovery can then also be done through conventional metallurgical means.

Observed co-benefits and limitations

Agroecological phytomining cropping systems permit the parallel cultivation of phytomining crops with conventional crops, which could provide additional benefits to farmers. Plant intercropping or co-cropping can enhance habitats and biodiversity, as well as stimulate the microbial communities and improve soil quality and functions. Incorporating N_2-fixing legumes into the cropping system can result in less dependence on fertilizers and thereby can enhance resource efficiency, the CO_2-footprint and economic viability. Further, hyperaccumulator plants are strongly resistant to pests and thus help to reduce the need for pesticide application. Farmers could apply this technique to metal-rich land to recover metals as a source of income. In particular, nickel agromining is considered an economically viable technique applied to ultramafic land, including ultramafic quarries, and technosols containing industrial waste. Plants that accumulate more than 2% Ni in aboveground biomass yield 200-400 kg Ni per ha, which has a greater value than all common agricultural crops (Chaney and Mahoney, 2018). In addition, renewable energy can be produced from the biomass (combustion or pyrolysis).

Breeding of improved strains with higher yields of the phytoextracted element, as well as the improvement of methods to recover the agromined element(s) from plant biomass would further enhance the phytoextraction yield and financial feasibility (Bani et al., 2015 a,b).

Contribution of this NBS unit to the mitigation of urban circularity challenges

Phytoremediation is a NBS which can be applied to any brownfields in cities to revitalize the valuable resource that healthy soils represent, thus counteract "linear" land use, and enable urban greening and the exploitation of its co-benefits for the living quality in urban areas, as well as for urban agriculture. Phytomining is likely less widely applicable in cities because mining and smelting sites are typically located in rural areas, however, the cases of cities located in ultramafic areas where there is industrial or mining activities cannot be excluded (Osmani et al., 2018 a,b). Nevertheless, phytomining can contribute to supplying metals required for product value chains that ultimately reach cities and thus reduce imports of primary resources into the urban system. Consistently, by extracting metals from contaminated soils, phytomining enables the reuse of metals otherwise not utilized (wasted) and adversely impacting ecosystems.

3.3. Liquid and solid streams

3.3.1. Street trees / pocket garden / large parks

Working principles

Street trees, pocket gardens and large urban parks are recognized as NBS by the following European projects URBANGREENUP - New Strategy for Re-Naturing Cities through Nature-Based Solutions (https://cordis.europa.eu/project/id/730426/fr), NATURE4CITIES - Nature Based Solutions for re-naturing cities: knowledge diffusion and decision support platform through new collaborative models (https://cordis.europa.eu/project/id/730468), UNALAB - Urban Nature Labs (https://cordis.europa.eu/project/id/730052) and in the scientific literature Castellar et al. (2021). Street trees are defined as single or multiple trees planted, renewed or maintained along roads, cycle paths and footpaths. Suitable species must be selected for specific locations. Trees may be placed on one side of the road as single row trees and on both sides of the road to form a boulevard, if appropriate. In this case, the canopies of opposite trees can form an (almost) closed canopy. Pocket or garden parks are publicly accessible compact green spaces or small gardens (< 0.5 ha) around and between buildings planted with ornamental trees, grass and other plant species. Large urban park refers to large green spaces (> 0.5 ha) within a city with a variety of active and passive recreational facilities that meet the recreational and social needs of residents and visitors to the city. They are open to a wide range of audiences. Also, these plants offer a wide range of additional services and can enable resource recovery including liquid, solid and gaseous streams (CO_2, etc.).

In and outputs

To function properly, street trees and plants established in pocket and large parks require a regular supply of nutrients and water. Nutrients can come from compost, organic or mineral fertilizers, or nutrient-rich irrigation water. Irrigation or fertigation water can be secondary treated municipal wastewater (e.g. output 2 of TW), rainwater, or other types of non-potable water. The amount of nutrients needed depends on the plant species and their nutrient requirements, as well as soil properties.

Output streams from street trees and parks are primarily cut branches, grass clippings, fallen leaves, seeds, and fruits that can be composted and returned to urban green spaces. While the above-ground woody biomass is not expected to accumulate pollutants (Landberg and Greger, 1996; Istenič et al., 2012), the leaf biomass may contain dust particles, heavy metals and PAHs (Thibodeaux and Mackay, 2011), and therefore the compost produced may not be suitable for food production and its quality needs to be analyzed prior further use. Leaves, seeds and fruits that fall on roads are removed by street cleaning and usually treated as mixed waste.

Case studies

In many cities (e.g. Vienna, Ljubljana; see Table 1) the municipal composting facility or waste utility collects green waste from parks maintenance, organic waste from public spaces and organic waste containers. The residents can also deliver garden waste on their own. The composting facility provides anaerobic digestion of organic matter and produces fresh compost, heath and biogas. Heat and biogas converted to electricity are used to run the composting facility. Fresh compost is available to residents free of charge or for a reasonable price.

Observed co-benefits and limitations

Street trees, large and pocket urban parks provide environmental, social and economic benefits. They reduce heat island effects as they are cooler than the surrounding due to evapotranspiration and shading; however, the size of the park and the tree species used impact the temperature differences (Bowler et al., 2010). Parks and street trees reduce air pollution by adsorbing particulate matter onto trees' and shrubs' surfaces, absorbing gases (O_3, NOx, SO_2, CO) and enable bio- and photodegradation of organic pollutants such as PAH thus reducing their further migration along the urban cycles and food chains (Bolund and Hunhammar, 1999, Terzaghi et al., 2020). Furthermore, they contribute to noise reduction; however, the density of vegetation, species, distance from the noise, ground surface features as well as subjective noise perception of residents impact the size of noise reduction (Fang and Ling, 1999; Koprowska et al., 2018). Street trees and parks significantly reduce rainwater runoff thus reducing urban flood risks and pressure on the sewage/stormwater collection and treatment systems (Armson et al., 2013). By regulating microclimate, urban water cycle and water treatment, street trees and urban parks can also mitigate extreme weather events and their consequences (Constanca et al., 2006).

Large urban parks and pocket gardens provide space for recreation and social gatherings and events and contribute to human physical and psychological health (Chiesura, 2004).

While biomass from urban parks and street trees is still mainly unexploited resource the studies show it can significantly contribute to renewable energy needs (Springer, 2012; Ferla et al., 2020); moreover, selected parts of parks can be used for growing energy crops which can reduce the maintenance costs and increase the renewable energy provision of the park (Sikorska et al., 2020).

Trees in pocket gardens, parks and tree-lined streets can temporarily contribute to capture and store CO_2 emissions and thus reduce the city's carbon footprint. Trees in cities can sequestrate 0.61 % of the annual traffic emissions as shown on the example of Meran in Italy. This result also depends on the further biomass use / treatment (Speak, 2020). Chen (2015) estimates that the green infrastructure of 35 cities in Chinas major cities could in summary sequestrate 0.33 % of the fossil fuel carbon emissions. The carbon storage calculations of urban trees can be very inaccurate and vary vastly depending on the management of the green spaces (Timilsina, 2014).

A comprehensive overview of regulating, provisioning, habitat and cultural ecosystem services and disservices of street trees including suggested management approached to maximize the benefits and reduce the limitations is provided by Sämuel et al. (2016).

Street trees and urban parks have numerous co-benefits; however, if not designed and operated in terms of circularity approach, they can also present certain disservices such as ecological (high water and nutrient demand), economic (leaf litter removal), social (undesirable insects and invasive plants), and public health (allergenic pollen) (Seamans, 2013) thus urban planning needs to find a balance between providing co-benefits as much as possible while at the same time minimizing the disservices to acceptable level (Döhren and Hasse, 2019).

Contribution of this NBS unit to the mitigation of urban circularity challenges

Most recognizable contribution of street trees, large and pocket parks to urban circularity challenges is their mitigation of urban runoff and thus restoration and maintaining of urban water cycle. Stormwater treatment and retention ponds, swales and other measures of sustainable urban drainage can be integrated with street trees and urban parks creating a multifunctional urban ecosystem. Especially in water deficit areas, irrigation of urban parks with reclaimed water providing water and nutrients for plant growth is a common practice (e.g. Wang et al., 2014; Zalacain et al., 2019).

Trees and parks are also applied to restore degraded building or district areas and recover their socio-economic function (Song et al., 2019). Additionally, street trees and urban parks are a low-cost source of lignocellulose-rich wastes that can be up-cycled to produce bio-composites (Viretto et al., 2021) thus contributing to material recovery and reuse. Parts of urban parks can be arranged as community gardens providing vegetables, fruits and herbs addressing urban challenge of food production (Sartison and Artmann, 2020).

3.4. Gaseous streams

Working principle

The ever-increasing growth in urban populations significantly intensifies anthropogenic effects on ecological systems, increases aerosols, particulate matter and greenhouse gas emissions from heating, ventilation and air conditioning (HVACs), traffic and power generation, resulting in thermal hotspots and continuous rise of CO_2 levels in cities.

CO_2 is an essential ingredient for photosynthesis. Vegetation as well as (micro)algae-based technologies can turn CO_2 into biomass. Carbon capture mechanisms (CCM) of algae (including cyanobacteria, a.k.a blue-green algae) supersedes CO_2 utilization of higher plants. When connected with photobioreactor systems, algae-based CO_2 capture can go above ambient atmospheric levels. As such, higher CO_2 releases in urban settings such as industrial flue-gas, transportation exhaust, broilers, etc. can be mitigated.

Meanwhile, waste from pruning vegetation and algae biomass can also be harvested and processed to fertilizer (compost, biochar) or bioenergy (Timilsina et al., 2014). Russo et al. (2015) reported that trees in the streetscapes of the city of Bolzano, Italy, annually offset 0.08% of the amount of CO_2 emitted by the transportation sector. CO_2 sequestration by trees per m^2 of canopy cover were reported from 0.56 kg/year in bicycle lanes to 0.92 kg/year in streets (Russo et al., 2015).

Anderson and Gough (2020) conducted a field study in Ontario, Canada, evaluating the impact of multiple green infrastructure applications on reducing ozone, nitrogen dioxide and CO_2 concentrations across urban, suburban and peri-urban morphologies. Data was collected from June to October over nine sites with mixed categories of five green infrastructure including green roofs, green walls, urban vegetation and forestry, urban agriculture systems, and tree-based intercropping systems. Results suggested that the application of green infrastructure across different urban, suburban and peri-urban morphologies is beneficial in reducing CO_2, ozone and nitrogen dioxide (Anderson and Gough, 2020). Though limited to one summer season, they detected an average reduction of 0.01, 0.11 and 23.4 ppm for ozone, nitrogen dioxide and CO_2, respectively, across all sites and green infrastructure applications (Anderson and Gough, 2020).

CO_2 exhaust gas from industrial plants can be used to enhance plant growth. Increasing CO_2-concentrations in greenhouses is a commonly accepted technique to promote photosynthesis (Dion et al., 2011), resulting in more sugars and carbohydrates produced by the plant, resulting in shorter production time as well as increased yields and income (Chalabi et al., 2002; Dion et al., 2011; Jaffrin et al., 2003; Sánchez-Guerrero et al., 2009; Tisserat et al., 2008). CO_2-supplementation can help to balance out CO_2-deficiencies that occur during the day in poorly ventilated greenhouses and thereby accelerate plant growth. This CO_2 could be added using waste exhaust gases, in particular enrichment from exhaust gases compared to pure CO_2 (Chalabi et al., 2002) and thus mitigating carbon emissions by capturing CO_2 in plant biomass (Dion et al., 2011). Also, the use of purified exhaust gas from biogas combustion for CO_2 supplementation in greenhouses has been demonstrated (Jaffrin et al., 2003). This contributes to closing the carbon cycle by capturing and utilizing CO_2 for production of food and industrial crops.

Reforestation and reducing deforestation and forest degradation (REDD) are eligible for carbon trading (IPCC, 2007) and could thus represent an additional pathway to valorize CO_2 that is metabolized by urban or peri-urban forests. Nath et al. (2015) highlight the high potential of timber bamboos for carbon farming and carbon trading due to the fast growth of bamboo and hence fast biomass accumulation. Timber bamboo captures 4.9-6 times the carbon that wood does (Hinkle et al., 2019).

In- and outputs

Potential in- and output flows of vegetation for CO_2 capture correspond to those as outlined in section 3.3 above. With respect to gaseous "resources", inputs include CO_2 and other air pollutants, introduced with the ambient air or exhaust gases directed to enclosed greenhouses. When photobioreactors are utilized for the cultivation of algae as described in 3.1.2, CO_2 enriched-air supply, NOx, SOx, VOCs can be managed inputs. With proper process control (pH, temperature, light, etc.), significant amounts of CO_2 capture can be achieved.

In addition to outputs listed in section 3.1.2, outputs will include O_2 and biomass which can be utilized for biomass-to-bioenergy routes.

Connected Units

NBS units providing inputs to vegetated CO_2 capture include those producing soil amendments (e.g. composting), treatment wetlands and photobioreactors, which can provide treated wastewater for irrigation, as well as anaerobic treatment units, which can provide treated wastewater or digestate (nutrient source). NBS using residues of urban greening include composting. Photobioreactors include tubular or panel type designs as well as open pond designs. For output connections, units can vary depending on final usage. When algal biomass is considered for liquid biofertilizer applications for city parks and other vegetation applications, no additional NBS units are required. However, anaerobic treatment units will be required for biogas/biomethane and subsequent compost applications.

Literature case studies

The famous 'vertical forest' (Bosco Verticale), an apartment building in Milan, features 20,000 plants, including 800 trees. It annually absorbs 40 tons of CO_2 and 1.5 tons of fine particulate matter each year, and generates 90 tons of oxygen per year (Bezemer, 2017).

The discharge of CO_2-enriched exhaust gases into greenhouses for yield increase has been demonstrated e.g. by Jaffrin et al. (2003), who directed landfill biogas into a combustion boiler that directed the CO_2 inside a greenhouse after being purified. Thus, the waste gas was used both for heating the greenhouse and as a source of CO_2 supplementation to enhance plant growth (Jaffrin et al., 2003).

Famous algae house (a.k.a. BIQ house) is a great example of CO_2 mitigation of urban buildings where broiler exhaust was in photobioreactors designed and installed as facades (https://www.buildup.eu/en/practices/cases/biq-house-first-algae-powered-building-world). PhotoSynthetica™ initiated by London-based Synthetic Landscapes Lab has several case studies demonstrating oxygen generating such as Algae Curtain displayed in November 2018 at Dublin Castle during the week of Climate Innovation Summit in Dublin (https://www.photosynthetica.co.uk/cladding). Another notable case study is demonstrated by The Cloud Collective's Culture Urbaine Genève where photobioreactors were attached to the concrete siding of a viaduct highway to capture CO_2 from overpassing vehicles (https://inhabitat.com/overpass-algae-garden-turns-co2-emissions-into-combustible-biomass-in-switzerland/).

Benefits and limitations

The plentiful co-benefits of urban greening are outlined in section 3.3 above. The effectiveness depends significantly on design specifications such as number of plants, growth conditions, species. Velasco et al. (2016) measured net CO_2 fluxes in subtropical and temperate urban areas, considering both vegetation and soil in combination. They found that urban greening reduced total CO_2 flux by 1.4% in a neighborhood of Mexico City, but added 4.4% extra CO_2 in a neighborhood in Singapore. They suggest that more complete assessments are needed to understand the lifecycle carbon reductions. Meanwhile, utilizing exhaust gases as a CO_2 source to measurably enhance crop production suggests that CO_2 is valorized that would otherwise be emitted to the atmosphere without further use.

As mentioned earlier algae can mitigate significant amounts of CO_2 from urban environments helping decrease overall carbon footprint of cities. Rather than costly carbon capture and sequestration (CCS) technologies, algae provide carbon capture and utilization (CCU) where additional value-added products such as biofertilizers and animal feed. These not only help municipalities decrease their costs, but also provide additional CO_2 capture as emissions generated during the manufacturing of the replaced product is avoided.

Meanwhile, as fast-growing living organisms, algae based NBS units require routine maintenance and equipment/processes in place to make use of generated biomass. Once a cycle is completed in set NBS units, seed cultures to initiate new batches must be available. Lastly, for building applications, appropriate measures must be taken to minimize or eliminate pumping noise of photobioreactors.

4. Supporting units

4.1. Physical separation units

Starting from the conventional flush toilet (A, top left), Figure 4 categorizes the current existing toilet- and urinal types that can be used as supporting units in connection with NBS.

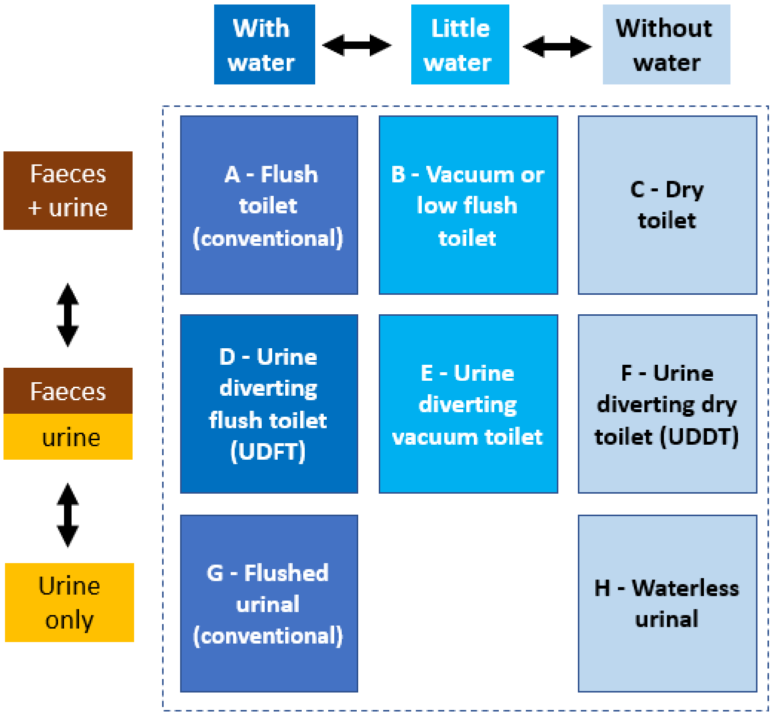

Figure 4. Toilets and urinals, categorized by water use and urine diversion. Grey: currently used toilet and urinal types.

4.1.1. Water saving/water-free toilets without urine diversion

Working principle

The basic principle of water saving (Figure 4 Type B) and dry toilets (Figure 4 Type C) is the reduction or complete absence of water as flushing medium and to pure(r) products.

In- and outputs

The inputs are urine, faeces, supporting materials (toilet paper, bulk material in dry toilets) and water (in low-flush toilets). The outputs of water saving toilets are a mixture of urine, faecal matter cleansing material and water. The outputs of dry toilets are a mixture of urine, faeces, cleansing materials and bulk material. The faecal flow can be contaminated with other substances beyond the design purpose, such as vomit, pieces of plastics or hygiene articles, or unwanted materials (e.g., bedding for cat toilets). Blackwater and dry toilet material contain pathogens and microcontaminants, e.g., pharmaceuticals and hormones and detergents.

Connected Units

The collected stream from water-saving or water-free toilets can be treated by anaerobic digestion (NBS 26) and subsequently nitrogen and phosphorus recovery SU 3 and SU 4) or by hydrothermal carbonization (SU 6). In case of dry toilets, the faecal matter plus urine can be transferred to a solid-state anaerobic digestion process (added NBS unit, derived from NBS 26), composting unit (NBS 23) or to a black soldier fly unit (added NBS unit). The dry faecal matter can also be dried and processed by pyrolysis (SU 6) The solid phase of anaerobic digestion (sludge), potentially after further drying and disinfection, or the processed dry toilet substrate can be used for soil improvement/slow-release fertilizer and conservation measures (NBS 33), or be subject to mechanical processing (added supporting unit) and, i.e., compost sieving (dry toilets).

Literature case studies

In Cressy (Geneva, Switzerland) the cooperative society 'Cooperative Equilibre'(CE) realized a three-storey/13-apartment building in 2011, which separates toilet waste from the water cycle by using dry toilets (Figure 4 Type C). Since 2011, CE has realized two more projects with a total of 103 apartments in Geneva following the idea of decentralized sanitation (including dry toilets) in an urban setting (https://www.cooperative-equilibre.ch/projets/cressy/, Kisser et al. 2020). Vacuum toilets followed by anaerobic treatment and nutrient recovery are applied in several so-called new sanitation projects in Germany, The Netherlands, Belgium and Sweden (Zeeman, 2012; Bisschops et al., 2020).

4.1.2. Urine diverting toilets

Working principle

The common principle of all urine diverting toilets (Figure 4, Types D-F) is the physical separation of the urine and faeces flows within the toilet. This common principle is materialized in different ways, depending on cultural practices (e.g., sitting vs. squatting), the presence or absence of water as flushing agent and by technical and design considerations (WEDC 2014). The development is ongoing. Recently a new, promising urine diverting toilet has been developed and tested, based on computational fluid dynamics (Gundlach et al., 2021).

In- and outputs

The inputs are urine, faeces, supporting materials (toilet paper, bulk material in dry toilets) and water (in flush toilets). The outputs of urine diverting dry toilets (Figure 4, Type F) are a) separated urine and b) faecal matter mixed with cleansing agents and bulk material. The outputs of flush toilets (Figure 4, Types D+E) are a) separated urine with no or little water and b) faeces with toilet paper and water. The faecal flow can be contaminated with other substances beyond the design purpose, such as urine, vomit, pieces of plastics or hygiene articles, or unwanted materials (e.g., bedding for cat toilets). The urine can also become cross contaminated with faeces. Blackwater and dry toilet material contain pathogens and microcontaminants (e.g., pharmaceuticals and hormones). Urine contains microcontaminants (e.g., pharmaceuticals and hormones) and, when contacted with faecal matter or excreted by people with a urinal infection, also pathogens.

Connected Units

The urine stream of urine diverting toilets can be connected to a storage tank as Supporting Unit for Solid/liquid separation (SU 7) as described in Langergraber et al., 2021 and subsequently brought to a struvite precipitation unit for phosphorus recovery (SU 3). For nitrogen, ammonia stripping/adsorption (SU 4/ SU 9) or the VUNA process (SU 4) are an option. The following connecting units have been identified for the processed urine: street trees and urban parks (fertigation, fertilization) (NBS 39, NBS 40, NBS 41), urban agriculture (NBS 49, NBS 50, NBS 51) and TW (NBS 21). For the solid phase the connecting units are identical with those of water saving/water free toilets (see 4.1.1). The brown water produced in flushed urine diverting streams can be treated either anaerobically or aerobically, depending on the amount of water used for flushing. So far, this latter stream is discharged in the sewer for transport and treatment in a conventional central aerobic system. For full circularity brown water also needs to be treated locally and should include resource recovery and reuse.

Literature case studies

At the Forum Chriesbach office building in Duebendorf, Switzerland, a urine nutrient recovery system with UDFT for 220 people has been in operation since 2012 (Eawag, 2019).

4.1.3. Water-free urinal

Working principle

The common working principle of water free urinals (Figure 4, type H) is the collection of urine without any addition of flush water. This common principle is materialized in different ways, depending on the design. Key characteristic of a water-free urinal is a device to allow free flow of the urine and at the same time prevent odor from the piping and storage to escape via the urinal.

In- and outputs

Input to the system is urine. As so far only water-free urinals for men are available, the input is limited to male urine. The output is characterized by concentrated urine without any water, except for cleaning. Urine contains microcontaminants (e.g., pharmaceuticals and hormones) and, when contacted with faecal matter or excreted by people with a urinal infection, also pathogens.

Connected Units

While water-free urinals are widely used in Europe today, water-free urinals are applied and connected to a storage tank only in a few office buildings. There, the collected urine is subsequently brought to a struvite precipitation unit for phosphorus recovery (SU 3). Nitrogen is so far not recovered, but ammonia stripping/adsorption or the VUNA process could be an option (SU 4). In general, the connecting units are identical with those of water saving/water-free toilets (see 4.1.1)

Literature case studies

Water-free urinals are installed in the office Rijnstraat, The Hague. Urine is after storage treated for struvite precipitation (https://www.desah.nl/en/products/realisation/government-building-the-hague-nl.html) and also at the EAWAG building Forum Chriesbach. Another case in Netherlands with water free urinals installed on a building scale is AFAS-LIFE. Urine is stored and transported to the wastewater treatment plant of Amsterdam, Waternet, for struvite precipitation (https://hollandcircularhotspot.nl/case/fosvaatje/). At the time of writing, it is not clear (yet) whether the recovery of P from AFAS-LIFE urine will be continued**.** Furthermore, the connecting units are potentially identical to those of the liquid phase of urine diverting toilets (see 4.1.2).

4.1.4. Benefits and limitations of water-saving and water free urinals and toilets

One main benefit of water saving (Figure 4, Types B+E), water-free (Figure 4, Types C+F) and urine diverting toilets (Figure 4, Types D-F) is the reduction or complete avoidance of flush water to enable energy efficient recovery of included resources. The quality of the outgoing flux depends largely on user behavior (e.g., proper use of toilet).

Vacuum toilets and dry toilets are both dependent on electricity. Vacuum toilets rely on a working vacuum system. Dry toilets need a constant air flow to keep odors out of the building, and regular handling for aeration and maturation of the compost, when directly connected with a composting unit. The main limitation is that the quality of the outgoing flux depends largely on user behavior (e.g., proper use of toilet).

The main benefit of successful waterless urine diversion toilets (Figure 4, Type F) or waterless urinals (Figure 4, Type H) is a much lower water consumption (on average, a person uses the toilet 5 times a day for urine production) and a concentrated, undiluted urine stock that can then be further processed by nitrogen and phosphorus recovery for fertilizer production. However, the quality of the outgoing flux depends largely on user behavior (e.g., proper use of toilet) and to a minor extent on technical materialization (e.g., existence of special toilet seats for kids). Urine contains microcontaminants (e.g., pharmaceuticals and hormones) and, when contacted with faecal matter or excreted by people with a urinal infection, also pathogens.

When combining water free urinals and vacuum toilets in, for example, an office building, the vacuum collected black water is extra concentrated because it is not diluted by (half of) the urine and the associated flush water.

4.2. Bio-physical units

4.2.1. Bioengineering

Working principle

Bioengineering uses vegetation within a "live" structure or "green" infrastructure system (Nora et al., 2008) and is applied as a building material for slope stabilization, e.g., for mitigation of landslides, stabilization of river banks, to control sediment runoff, erosion and flooding, and to enhance biodiversity (Mickovski et al., 2021). Bioengineering techniques use live materials in combination with dead and inorganic materials (brush mattresses, geotextiles, fascines, wattle or wicker fences, hedge layers, branches).

In- and outputs

Bioengineered structures may require irrigation, at least in the initial growth phase. This could be provided by rainwater or treated wastewater. Nutrients could be provided by secondary sources recovered by NBS like water recovery from grey water treatment.

Bioengineered surfaces and slopes can retain rainwater and treat urban surface waters such as rivers (Jablónska et al., 2020), and thereby provide water fit for multiple reuses. Bioengineering also provides a stable foundation for other NBS. Depending on the design, the vegetation can store large amounts of CO_2 as biomass (Fortier et al., 2015), which could be used as a source of organic carbon and nutrients (as compost or biochar), or bioenergy.

Connected Units

Bioengineering can support soil conservation and phytomining (section 3.2), as well as street trees, pocket gardens, large parks (section 3.3) by providing slope stabilization, preventing erosion and providing ecosystem services including nutrient capture from water sources. Bioengineering can also be a form of vegetated carbon capture system (section 3.4).

Literature case studies

Bioengineering is applied to a larger extent in rural areas, but its benefits have been recognized also for cities. For example, for the construction of the Kartalpe metro station in Istanbul, Turkey, 0-25 m of topsoil were excavated and removed from a hill resulting in serious erosion. A rehabilitation project applied bioengineering techniques to stabilize the slopes and re-vegetated them (ECOMED, 2017 - https://ecomedbio.eu/case-studies-fluvial-coastal-slope).

Benefits and limitations

Benefits include carbon storage as biomass (Fortier et al., 2015), ecosystem services of urban greening, as well as nutrient removal from rivers in the case of vegetated riverbanks (Jablónska et al., 2020). Compared to softwood river bank stabilization (using brush mattresses, willow species), reed performed the highest nutrient retention and carbon sequestration in biomass in a study by Symmank et al. (2020) in Germany. Recovered products should meet the demands with respect to quality (e.g., concentrations of pathogens and micropollutants, and requirements with respect to nutrient content).

4.3. Post- and pre-treatment units

4.3.1. Disinfection (UV, cavitation)

Working principles

Disinfection is a process of adding chemical agent(s) into drinking water to inactivate pathogen microorganisms – parasites, bacteria and viruses (EPA, 2021). Chlorine gas and chlorine dioxide are the most widely used disinfectants, while other forms of chlorine such as monochloramine (NH_2Cl) and dichloramine ($NHCl_2$) are used to a limited extent. The main principle of reaction is based on the formation of chlorine free radical (i.e., Cl_2 molecule form two Cl atoms, initiated by UV radiation or sunlight; where further Cl atom has an unpaired electron and acts as a free ·Cl radical). Beside chlorination, the most commonly used disinfection processes are: UV-radiation, solar disinfection, cavitation, multiple disinfectants (TiO_2/Ag^+) and ozonation, among others (Bond et al., 2014). Ozone-disinfection, extensively used in Europe, is based on the fact that ozone is a strong oxidative agent (E_{red}= 2.08 V) and may react with substrates both via reactive O_3 species and hydroxyl radicals (·OH) generated by the decomposition of ozone (Miklos et al., 2018).

In- and outputs

The amount/dose of applied chlorine depends on the type of chlorine disinfection: the added dose of active chlorine is between 2 and 5 mg L^{-1}, and after chlorination the outlet should be between 0.2 and 0.5 mg L^{-1} (PSATS, 2016). The advantage of chlorination over ozonation is the prolonged, residual effect of chlorine derivatives into the distribution system. Ozone is generated onsite because it is unstable and decomposes to elemental oxygen in a short amount of time after generation (US EPA, 1999). Ozone may be added at several points throughout the treatment system, such as during pre-oxidation, intermediate oxidation or final disinfection.

Connected Units

Various types of injection kits and pumps are used for the water disinfection; the proper point of injection into the flow stream and thorough mixing is essential for full treatment (PSATS, 2016). The operational site for chlorination/ozonation has to be equipped by: electric sources, adequate ventilation, but also requires location relatively free of dust and dirt, protected from excessive sunlight or freezing. The disinfection area has easy access for maintenance and refilling; and, if using a chemical tank, the tank has to be positioned as close as possible to the feeder.

Literature case studies

The occurrence and fate of carbonyl compounds as ozonation by-products at a full-scale drinking water treatment plant (DWTP) were studied for raw water and treated effluents (pre-ozonation, coagulation/flocculation, sand filtration, main ozonation, filtration through granular activated carbon and chlorination), on a monthly basis (Papageorgiou et al., 2014). Pre-ozonation led to the formation of carbonyl compounds at concentrations of 67.3 ± 43.3 μg L^{-1}(as a sum of 14 carbonyl compounds), whereas lower concentrations were determined after the main ozonation process, measured at 32.8 ± 22.3 μg L^{-1}. Moreover, the effective microbiological disinfection of drinking water may be also achieved with lower concentration of ozone in shorter contact time compared to other disinfectants, such as chlorine, chlorine dioxide and monochloramine (von Sonntag et al., 2012).

Benefits and limitations

The reaction between organic molecule and chlorine during water treatment results in potentially-hazardous disinfection by-products (DBPs) (Richardson et al., 2000). Over 600 chemicals are classified as DBPs (Krasner, 2009), among which the most hazardous compounds are known as trihalomethanes (THMs) (Li et al., 2017). According to the United States Environmental Protection Agency (US EPA), the maximum contaminant level of four chlorinated and/or brominated THMs in drinking water is regulated at 100 μgL^{-1} (US EPA 2018). A range of low molecular-weight carbonyl compounds (i.e., aldehydes, ketones and carboxylic acids) are expected by-products of this partial oxidation. Since ozone transformation products can either have a higher or lower tendency to generate DBPs than the starting material, contrasting effects on DBP formation are also unsurprising (Bond et al., 2014).

4.3.2. Activated carbon

Working principle

Adsorption is a chemical process used to remove a wide range of pollutants, both organic and inorganic, from liquid and gaseous flows. Most common adsorption systems use granular activated carbon (GAC) in column reactors because they are efficient and relatively cheap and simple to operate. GAC can be produced from different carbonaceous materials as wood, coke, coal and agricultural residues (Marsh and Reinoso, 2006). The pressurized downflow columns are the most common solution for water treatment; in this case, GAC acts as filter and more frequent backwashing is necessary (Chowdhury, 2013).

In- and outputs

Activated carbon adsorption can be adopted as the final step of plants treating municipal wastewater, greywater, blackwater, urine or stormwater. It is mainly applied to remove organic micropollutants such as pharmaceuticals, personal care products, pesticides and other industrial additives (Reyes Contreras, 2019). Treating secondary wastewater effluents with activated carbon results in a high-quality effluent that can be reused for many purposes. When the adsorption capacity of the GAC runs out, it is removed and sent to thermal regeneration.

Connected Units

GAC adsorption can be used to treat effluent of TW (NBS 21), PBR (NBS 48), wastewater aerobic treatment processes (NBS 26). It produces effluent that can be used to irrigate street tree/road vegetation, large urban park and pocket gardens (NBS 39, NBS 40, NBS 41).

Literature case studies

Bourgin et al. (2018) investigated how WWTPs (upgraded by an advanced treatment for micropollutant abatement with (powdered) activated carbon treatment and/or ozonation could perform in reducing the discharge of micropollutants from WWTPs. The activated carbon filtration ensured a significant additional micropollutants abatement after ozonation due to sorption oxidation by-products (OBPs) such as bromate (BrO_3^-) and N-nitrosodimethylamine (NDMA) which allows to protect the ecosystem and drinking water resources in Switzerland.

The Pharmafilter pilot scale installation (https://www.stowa.nl/publicaties/evaluation-report-pharmafilter) treats hospital wastewater for reuse and converts organic solid materials to energy. The core of the technical wastewater installation is the collection and treatment of wastewater to which other hospital waste flows have added, and includes the use of single use biodegradable solid products. The following processing steps take place in the installation: i) shredding and separation, ii) sieving over the grid, iii) mixing/hydrolysis and digestion, iv) membrane bioreactor, v) high flux ozone installation, vi) activated carbon, vii) extraction and treatment of air, viii) monitoring and control. The ozone treatment may not remove all the micropollutants (pharmaceuticals, X-ray contrast fluids, etc.) and may convert an unknow number into metabolites which may unfavorably affect the aqueous environment in which the treated wastewater is discharges. Activated carbon is therefore used as an extra stage to remove residues of pharmaceuticals, oxidation by-products and hormone disturbing substances that have passed through the ozone stage. Batelaan et al. (2013) have reported that activated carbon filtration of ozone treated effluent is acting as a good barrier to micropollutants. In another study, Duygan et al. (2021) demonstrated that to reliably remove pharmaceuticals from treated urine, a post-treatment using adsorption to powdered activated carbon (PAC) was required. A risk assessment of the treated urine used as fertilizer on soil resulted in a risk quotient below 1 for the concentrations of trimethoprim, diclofenac, and sulfamethoxazole predicted in European countries and the USA. These results, and results from another study using granular activated carbon (Köpping et al., 2020) have led to the production of a urine fertilizer (named Aurin), that is authorized for use on vegetables and flowers in Switzerland (Vuna GmbH 2020).

Benefits and limitations

The main advantage of PAC/GAC adsorption is that it can simultaneously remove a large variety of inorganic and organic micropollutants, including disinfection by-products. It is also able to partially remove some pathogens. The main disadvantage is that the activated carbon runs out and must be replaced with a frequency that depends on the contamination degree of the fluid treated. Finally, it must be noted that a granular filtration section is necessary upstream GAC filters to remove total suspended solids.

4.3.3. Advanced oxidation processes (AOPs)

Working principles

Advanced oxidation processes (AOPs) are frequently reported to be among the most suitable water treatment technologies to remove natural organic matter (NOM) and micropollutants (MPs) from wastewater (Rizzo et al., 2018). The main principle of AOPs degradation is reaction of organic molecules (NOM & MPs) with hydroxyl radicals (°OH), resulting in formation of smaller molecules (with consequently, smaller number of C atoms); °OH radicals are defined as the strongest reactive species that can oxidize any compound present in the water matrix (Miklos et al., 2018). NOM, as a complex matrix of organic substances, is characterized by its variable molecular and physico-chemical properties caused by various solid-liquid interactions (bio-geologic formation and hydrologic cycle) (Sillanpaa et al., 2018). MPs are usually found in aquatic medium at very low concentrations (ng L^{-1} - μg L^{-1}) and known as xenobiotic compounds, such as pharmaceuticals, personal care products, steroid hormones, drugs of abuse, and pesticides, among others (EU, 2018).

In- and out puts

Despite the ability of a vast number of microorganisms to degrade a wide diversity of MPs (in convention wastewater treatment plants), the residual concentration of these compounds in wastewater may be due to their low bioavailability in biological reactors (Nunes, 2020). Consequently, the secondary wastewater effluents of convention activated sludge treatment still contain numerous MPs. In order to abate the presence of these compounds, the advanced oxidation processes such as: i) UV/H_2O_2 (Ceretta et al., 2019), UV/chlorine (Kishimoto, 2019) and/or ozone-based applications (O_3/H_2O_2 and O_3/UV) (Wang, 2017), ii) photo Fenton processes (Vilar et al., 2012) and various electro-catalytic processes Yang, 2019), are applied (or tested at pilot scale). Hence, the AOP are found to fill the gap between the conventional physico-chemical and biological treatments and the limits set by environmental regulations (i.e., the degree of contamination of the treated wastewater determined by its end/use or site of discharge) (Dewil et al., 2017).

Literature case studies

Developing countries, or even developed ones whose infrastructure is in decline, have dissimilar challenges concerning urban pollution prevention and control (Markovski et al., 2015). These range from providing basic access to safe drinking water and improving essential wastewater treatment. Outdated sewage systems that do not incorporate any wastewater treatment (such as is the case in some of Western Balkan countries), as well as wastewater treatment infrastructure not designed to cope with an ever-growing number of MPs, are the main culprits in the deterioration of water quality. However, although AOP have been effectively tested (EU pilot scales) in the degradation of xenobiotic removal, particularly homogeneous photo driven AOPs (e.g., UV/H_2O_2 and photo-Fenton) and heterogeneous photocatalytic processes (e.g., UV/TiO_2), do not yet find their application at full scale in urban wastewater treatment (Rizzo et al., 2018). Ozone doses and contact times during advanced water treatment, which typically vary in the range of 1–5 mg L^{-1} and 15–30 min respectively, are usually insufficient to completely mineralize NOM (Singer et al., 1999).

Benefits & limitations

One of the main advantages of AOPs is their capacity to simultaneously disinfect water. Hence, besides degrading organic pollutants (NOM & MPs), the mechanism for microbial inactivation used by AOP (i.e., the oxidative stress generated by ozonation) is also capable to reduce the microbial load of wastewater. Since the ozonation may result in the formation of oxidation/disinfection by-products (e.g., N-nitrosodimethylamine (NDMA) a bromate), a polishing post-treatment step with biological active sand filter is recommended (von Gunten, 2018).

4.4. Resource recovery supporting units

4.4.1. Phosphorus precipitation

Working principle

P-precipitation is generally established by addition of multivalent metal ions like calcium, magnesium, aluminium and iron. Calcium and magnesium are generally applied when reuse of the precipitate is aimed at struvite precipitation using magnesium is so far mostly applied for P recovery from concentrated streams, like anaerobically treated black water or stored urine (de Graaff et al, 2011). More information on struvite precipitation is reported in: https://run4life-project.eu/wp-content/uploads/2020/08/H2020-Run4Life-Factsheet-Technology-Struvite-Precipitation.pdf. Cunha et al. (2017) show the possibility to produce calcium-phosphate granules in the anaerobic reactor (UASB) for treatment op blackwater, but latter process is so far only applied at laboratory scale.

In- and outputs

High P inputs streams are needed for an efficient struvite recovery. Applicable urban streams are anaerobically treated, vacuum collected blackwater with or without kitchen waste or separately collected urine, rejection water from digested sewage sludge.

Connected Units

When P is precipitated from urine, water free urinals or urine separation toilets followed by a storage unit are connected to the precipitation reactor, while anaerobic treatment is applied prior to the precipitation reactor when black water with or without kitchen waste is the phosphorus source. To ensure a sufficiently high concentration, the blackwater is collected with water saving vacuum toilets (maximum one liter per flush). Prior or after recovery of phosphorus, nitrogen recovery/removal is needed. In Helsingborg (H+) ammonia stripping/absorption is applied (see below), while in Sneek nitrogen is removed via the OLAND process (Vlaeminck et al., 2009). In Ghent, Nieuwe Dokkken, nitrogen is removed via conventional nitrification/denitrification applying the COD from greywater as a carbon source plus a waste product from the nearby detergent industry (https://run4life-project.eu/demosites/).

Literature case studies

Case studies were struvite precipitation is applied in the urban environment are Waterschoon in Sneek, a housing estate of 250 houses were source separated sanitation is applied (https://www.stowa.nl/sites/default/files/assets/PUBLICATIES/Publicaties%202018/STOWA%202018-63%20NS%20Noorderhoek.pdf), Rijnstraat in The Hague, an office where both urine and black water is separately collected. (Struvite is produced from urine), (https://www.nutrientplatform.org/succesverhalen/rijnstraat8/), H^+ in Helsinborg (https://run4life-project.eu/demosites/) and Nieuwe Dokken in Ghent (https://run4life-project.eu/demosites/), both recently built housing estates with ca. 2000 inhabitants applying source separated sanitation with struvite precipitation from digested black water plus kitchen waste.

Benefits and limitations

Benefits of the struvite precipitation process are the high recovery efficiency of phosphorus, a simple and stable process with low energy input and a proven and well-known technology (https://run4life-project.eu/wp-content/uploads/2020/08/H2020-Run4Life-Factsheet-Technology-Struvite-Precipitation.pdf).

The product struvite is a slow-release phosphorous fertilizer, to be used in agriculture. However, the low N:P ratio does not meet the requirements of most crops, therefore struvite is usually combined with nitrogen fertilizers (https://run4life-project.eu/wp-content/uploads/2017/10/H2020-Run4Life-Factsheet-Product-Struvite.pdf; https://run4life-project.eu/wp-content/uploads/2017/10/H2020-Run4Life-Factsheet-Product-NPK-Pellet.pdf). Incinerated CaP granules, produced during anaerobic blackwater treatment, can directly replace phosphate rock in the fertilizer industry (Cunha et al., 2020).

4.4.2. Ammonia stripping/absorption

Working principle

In the ammonia stripping process, wastewater and air are brought into contact to transfer ammonia from the liquid to the gas phase. To ensure a high NH_3/NH_4^+ ratio, the pH of the wastewater is increased by adding a base. The water and gas flow in opposite direction and the stripping tower generally contains packing material to enlarge the contact surface to maximize ammonia stripping.

To produce ammonium sulphate or ammonium nitrate, that can be used as a fertiliser, the ammonia rich air is scrubbed with nitric acid (HNO_3) or sulphuric acid (H_2SO_4). Further details can be found in: https://run4life-project.eu/wp-content/uploads/2020/08/H2020-Run4Life-Factsheet-Technology-Ammonium-Stripping.pdf

In- and outputs

Urban inputs of a stripping unit are high nitrogen containing streams like anaerobically treated, vacuum collected blackwater or urine. Urine has generally a higher nitrogen concentration as compared to anaerobically treated, vacuum collected blackwater.

Connected Units

The connected units are P-precipitation (struvite) and anaerobic treatment.

Literature case studies

So far ammonia stripping for N-recovery from urban streams applied in the city, is only executed in Helsingborg (https://run4life-project.eu/demosites/) for anaerobically treated vacuum collected blackwater. Urine generally has higher N concentrations as compared to vacuum collected black water but so far, the ammonia stripping process for urine was only applied on a pilot scale (Wei et al., 2018).

Benefits and limitations

The main benefit of the process is that a nitrogen fertilizer is being produced. For details on the product see: https://run4life-project.eu/wp-content/uploads/2017/10/H2020-Run4Life-Factsheet-Product-Ammonium-Sulphate.pdf. The limitation of the stripping process is that it needs a stream with a high nitrogen concentration for an energy efficient process performance.

4.4.3. Membranes

Working principle

Membrane separation processes such as low-pressure microfiltration (MF) and ultrafiltration (UF), or high-pressure nanofiltration (NF) and reverse osmosis (RO), utilize a physical permeable barrier that enables to treat water while rejecting pollutants. During membrane filtration, the membrane allows the passage of certain constituents and retain other constituents found in the liquid. The membranes may be operated separately or in combination with other processes as a part of hybrid systems such as membrane bioreactors (MBRs), combining biological treatment (for example as activated sludge) with MF or UF (Krzeminski et al., 2017; Masi et al., 2020). The type of membrane, and associated selective pore size, influences the types of pollutants removed from the water. MF and UF are commonly used for solids, polymers, emulsions, colloids, and bacteria (for disinfection purposes) removal. In UF also viruses and proteins are removed. NF and RO are used to reduce the effluent salinity or for removal of organic and inorganic contaminants, including emerging contaminants and antimicrobial resistance control (Warsinger et al., 2018; Rizzo et al., 2020). If membrane is supplied with aeration system, it may be used for nitrification and membrane aerated biological reactor (MABR) can be used for nitrogen removal where both nitrification and denitrification (with external carbon dosage) can be achieved in one unit (Houweling et al., 2017; Plaza et al., 2018; Tirosh & Shechter, 2020).

In- and outputs

The incoming stream can be either treated or untreated urban wastewater, greywater, blackwater, or stormwater. The outcome streams are reclaimed water (effluent, also referred to permeate) and concentrate stream with accumulated compounds not passing the membranes or, in case of MBR, the solids.

Membranes can be employed as a polishing step for further removal of specific contaminants and as such support the TWs, PBRs, or anaerobic treatment units. By using appropriate membrane type, membranes enable recovery of water with a quality tailored to the needs of the reuse application including potable water (Peter-Varbanets et al., 2009; Capodaglio, 2020). The reclaimed water produce can be used for irrigation or fertigation purposes (for example in street trees, urban parks, urban agriculture). Membranes may be also used for harvesting of algal biomass in PBRs or solid/liquid separation (SU 7) in anaerobic system without biomass retention (Zhang et al., 2010).

Connected Units

Membranes are versatile and membrane filtration units can be incorporated with other units in multiple configurations. Membranes can act as a pre-treatment, post-treatment, separation or up-concentration step.

Membrane unit can be combined with other solid/liquid separation units (SU 7), including other type of membranes, which can provide a pre-treatment function. Membranes may also be followed by a disinfection unit especially when membranes with more open structure, such as MF, are used and/or when water disinfection is of particular importance. Other units such as AOP or activated carbon may be connected for the post-treatment purposes to remove, for example, remaining organic matter (COD), residual contaminants (e.g., persistent pharmaceuticals, chemicals, etc.) or salinity.

Case studies and literature

Among different membrane systems, MBRs are most commonly used for treatment of domestic wastewater, greywater and/or combination of domestic greywaters and effluents from blackwater treatment (Fountoulakis et al., 2016; Matulova et al., 2010; Tai et al., 2014; Andersson et al., 2021).

Observed co-benefits and limitations

The main benefit of the membranes is high and stable quality of the produced water, enabling water reuse which contributes to closing the water cycle. Another benefit of the membranes is their small footprint and modularity suitable for all scales, including single household (Fountoulakis et al., 2016; Matulova et al., 2010). The typical drawbacks are high energy requirements (can be offset by the use of renewable energy sources or by gravity driven systems), the cost of membranes, membrane fouling, and generation of the concentrated stream containing the separated salts and other pollutants (which could be subsequently recovered with other potentially valuable materials).

4.4.4. Biochar/Hydrochar production

Working principle

Biochar and hydrochar are products of thermochemical processes of biomass conversion. Thermochemical processes include pyrolysis, torrefaction, gasification, or hydrothermal carbonization. For these processes, dry or wet organic carbon-rich material or C-rich biomass are required. The quality of their products (biochar or hydrochar production) depends on the type and the process conditions of thermochemical process. Processes that produce biochar include pyrolysis (heating without oxygen, dry oxygen –at poor environment at 200-900°C), torrefaction, and gasification; other coproducts include water vapor, heat, condensable liquids (bio-oil, condensable tar (that goes to landfill), and syngas (combustible gases such as CO, CH_4, H_2 for energy production). In the case of hydrochar production, usually the reaction pressure (hydrothermal carbonization) is not controlled in the process and is autogenic with the saturation vapor pressure of water corresponding to the reaction temperature. At high temperatures, water with high ionization constant can facilitate hydrolysis and cleavage of lignocellulosic biomass; water is responsible for hydrolysis of organics, which can further be catalyzed by acids or bases.

In- and outputs

Biochar is the char coproduct from the thermochemical processing of dry biomass. Biochar can be produced from different types of biomass residues, including crop plants (e.g., rice husk, wheat bran), tree cuttings, wood chips or dried fecal matter, such as composting toilet substrate (Bleuler et al. 2020) and as an intermediate product in bioethanol production (biowastes from the food processing industry).

The hydrothermal carbonization of C-rich biomass in the presence of water results in the production of a solid material that is referred to as hydrochar (Hu et al., 2010).

Literature case studies

Interest in biochar soil applications originated from the long-term fertility of terra preta anthropogenic soils in the Brazilian Amazon (Bettendorf et al., 2015). More recently, the recalcitrance of biochar carbon has attracted international attention as an inexpensive and effective way to sequester atmospheric carbon for centuries to millennia while simultaneously producing carbon-negative energy and improving soil quality (Glaser et al., 2009). Current research and demonstration cases focuses on relationships between feedstocks, reaction conditions, biochar properties, soil and crop responses to biochar applications and biochar economics (Hu et al., 2021).

Benefits and limitations

In general, thermo-chemical processes are attractive and have certain advantages such as higher productivity, complete utilization of feedstocks leading to multiple products, applicability to a wide range of feedstocks, independence of climatic conditions, and better control over the process relative to biological processes (Verma et al., 2012).

Biochar has been used primarily for soil remediation (e.g., Spokas et al. 2012) and as an agent for carbon sequestration (Woolf et al., 2010). Both biochar and hydrochar have value added industrial use, and both could increase carbon sequestration and nutrient recovery (because of the production of N-rich products). If used as soil physical and chemical improvers, biochar and hydrochar could both improve pesticide and nutrient management, increase soil carbon storage, enhance water infiltration and retention, encourage beneficial soil organisms and prevent soil compaction (Cao et al., 2009; Yao et al., 2011). On the other hand, they could be heavy metals sources and if used in high quantity as soil improvers, both biochar and hydrochar could increase albedo (first paper on this topic was written by Meyer et al., 2012).

The advantage of hydrothermal carbonization processes is that it usually takes place at relatively low temperatures (150-350°C, at about 2 MPa pressure) and wet feedstock can be directly used, including wet animal manures, sewage sludge, and algae (Xue et al., 2012). It is a fast process that has a much shorter residence time than dry pyrolysis. However, there are contrasting data on the consistency of the eco-friendly nature of the process even if tar is not produced and the reduced ash content.

5. Discussion

Table 1. : Summary of the NBS case studies reported in the present paper. 1819

Case study	NBS units	Supporting units	Product and reuse	References
Sneek – Noorderhoek, the Netherlands	Anaerobic BW treatment (UASB) Aerobic GW + effluent BW treatment OLAND (nitritation/anammox)	Vacuum toilets, struvite precipitation, membrane filtration	Biogas, Struvite, reclaimed water	https://www.saniwijzer.nl/
Lübeck, Flintenbreite, Germany	Vertical flow treatment wetland for greywater, anaerobic treatment for blackwater and biowaste	Vacuum toilet	Liquid biofertilizer for farmlands and gardens, reclaimed grew water for discharge and groundwater recharge	https://www.cyclifier.org/project/flintenbreite-neighborhood/ http://www.susana.org/_resources/documents/default/2-59-en-susana-cs-germany-luebeck-ecological-housing-bobx.pdf
Hannover, Germany	Treatment wetland for greywater	Vacuum toilet, urine diverting toilets	Reclaimed water for toilet flushing	https://www.susana.org/_resources/documents/default/2-1986-en-ecosan-pds-007-germany-hannover-oekotechnikpark-2005.pdf
Lima, Peru	Composting of organic waste, vermicomposting for solid fraction of blackwater, treatment wetland for greywater, treatment wetland for liquid fraction of blackwater	Urine diversion toilets, solid separation unit	Treated blackwater for irrigation of lawns, reclaimed greywater	https://www.susana.org/_resources/documents/default/2-70-en-susana-cs-peru-lima-sanchristoferus-2009.pdf
Grecia Salentina area, Italy	Composting from house organic waste; vermicomposting; home composting; community compost		Compost/vermicompost for home and city use	http://www.compostcommunity.it/wp-content/uploads/2021/01/brochure_inglese.pdf
Vienna, Austria	Anaerobic treatment and composting of kitchen waste and green waste from urban green areas		Compost for urban green areas, gardens	https://www.wenigermist.at/biomuell-und-speisereste-richtig-entsorgenvo-ka
Ljubljana, Slovenia	Anaerobic treatment and composting of kitchen waste and green waste from urban green areas		Compost for urban green areas, gardens	http://www.rcero-ljubljana.eu/
Mālpils, Latvia	Vermicomposting from different types of biowaste (e.g., sewage sludge, manure, leaves)		Compost for urban green areas, gardens	https://smartcitysweden.com/best-practice/192/biowaste-treatment-by-vermicomposting/

Culemborg, EVA-Lanxmeer, the Netherlands	VF treatment wetland (grey water)		Reclaimed water	https://edepot.wur.nl/180531 (in Dutch) https://www.urbangreenbluegrids.com/projects/eva-lanxmeer-results/
Cressy, Switzerland	Composting unit VF treatment wetland (greywater)	Dry toilet	Compost, reclaimed water	https://www.cooperative-equilibre.ch/projets/cressy/
Hamburg, Jenfelder au, Germany	Anaerobic treatment (CSTR)	Vacuum toilets	biogas	Hertel et al., 2015
Helsingborg, H+, Sweden	Anaerobic treatment (UASB); aerobic GW treatment	Vacuum toilet; struvite precipitation; ammonium stripper	Struvite, organic fertilizer, ammonium sulfate, biogas	http://run4lifeproject.eu/
Sneek Lemmerweg, the Netherlands	TAD (Thermophilic anaerobic treatment) (UASB)	Ultra-low flush vacuum toilet	Hygienized effluent containing fertilizers	Todt et al., 2021
Wageningen, NIOO, the Netherlands	Anaerobic treatment (UASB) Pilot Photobioreactor	Vacuum toilets	Biogas, algae biomass, reclaimed water	https://www.saniwijzer.nl/ (in Dutch)
Oslo, Klosterenga, Norway	Septic tank Aerobic biofilter Horizontal subsurface flow treatment wetland		Reclaimed water	https://www.susana.org https://www.susana.org/_resources/documents/default/2-248-jenssen-urban-greywater-oslo-en.pdf
Gent, Belgium	Anaerobic treatment Aerobic treatment	Struvite precipitation, Vacuum toilets, Membranes	Struvite; reclaimed water, biogas	http://run4lifeproject.eu/ Democase Gent - Nereus Project (nereus-project.eu)
The Hague, Rijnstraat, the Netherlandds	Anaerobic treatment	Struvite precipitation vacuum toilets Waterfree urinals	Struvite, biogas	http://www.saniwijzer.nl (in Dutch)
Hamburg, BIQ, International Building Exhibition (IBA), Germany	Photobioreactor	Flotation unit, heat exchanger, an external biogas plant	Algae biomass, heat for heating and sanitary water, heat and sound insulation	https://www.archdaily.com/339451/worlds-first-algae-bioreactor-facade-nears-complet
Tampere, algal ponds, Finland	Algae ponds	Source-separation of urine	Algal biomass for fertilizer use	https://www.vanajavesi.fi/levasieppari-hanke-ravinteet-talteen-ja-kiertoon-luonnonmukaisesti/
Berlin, Block 6, Germany	Blackwater treatment Greywater treatment Urban farming	Heat recovery from grey water	Heat and reclaimed water, organic fertilizer	http://www.roofwaterfarm.com/en/block-6/
Pogradec Albania-mineralized soil and Prrenjas,	Phytomining-Agromining	-	Nickel salt, energy, inorganic fertilizer	https://life-agromine.com/en/homepage/ Bani et al., 2021 Osmani et al., 2018a,b.

Elbasan Albania contaminated soil

The above described NBS and supporting units present a broad set of technologies and solutions which can provide a considerable degree of resource recovery within urban environments, from water to nutrients to inorganic constituents and energy. Nevertheless, NBS still present some limitations which prevent further implementation of these solutions in many settings.

For one, defining NBS is still a work in progress, and different organizations have taken to develop their own definitions. The European Commission within its' independent expert report defines NBS as "*inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience (…) solutions [which] bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions*" (European Commission, 2021). This somewhat differs from the definition developed within the COST Action Circular City framework in which this paper was developed. In it, NBS are described as "*concepts that bring nature into cities and those that are derived from nature (…) address societal challenges and enable resource recovery, climate mitigation and adaptation challenges, human well-being, ecosystem restoration and/or improved biodiversity status, within the urban ecosystems (…) definition we achieve resource recovery using organisms (e.g., microbes, algae, plants, insects, and worms) as the principal agents (…) [and] physical and chemical processes can be included for recovery of resources (…), as they may be needed for supporting and enhancing the performance of NBS*" (Langergraber et al., 2020). While the definition provided by the previous paper of the COST Action Circular City has to be considered within the context of achieving circularity in the specific environment of the city, this variation in definitions prevent a cohesive message to come across the wider community which need to finance, construct and maintain these NBS in the first place. The lack of a uniform definition may also limit the development of a legal framework, which in turn also increases the bureaucratic problems associated with this type of interventions.

Another limitation for resource recovery using NBS is that as observed in this paper, natural processes alone cannot achieve the necessary rates of recovery or provide the product in a retrievable form. In many cases, the resources used by the organisms of the NBS units are in normal conditions utilized for their natural growth (for example plant growth), but in most circumstances, NBS fail to provide the recovered nutrient or resource in pure form. Some notable exceptions do exist, such as anaerobic digestion, a process which results in the production of biogas, and food production by urban farming. The COST Action Circular City takes this into consideration, and the inclusion of the need for supporting physical and chemical processes is particularly relevant for the group which developed this paper. The various supporting units described in this paper can therefore provide alternatives which increase the rate of recovery of several nutrients, for example phosphorous through processes such as struvite precipitation, with no biological input, but which result in a recoverable and easily applicable product. The supporting units in this paper have proven to be able to refine the output materials from some NBS units into higher value products, and therefore provide greater efficiency and economic viability to a process which is still dominated by natural processes. However, a proper planning of the combination of NBS units and downstream supporting systems is required, in order to obtain good quality output materials. However, to achieve high quality end-products and high efficiencies, it is also necessary to have good source materials upstream. This can also be a limiting factor in achieving circular nature-based systems, as the modern configuration of many urban areas still approaches water resources as one stream, when in reality several higher purity (and quality) streams exist, such as stormwater, greywater, blackwater, etc (Oral et al., 2020; Besson et al., 2021). For many of the NBS described, the input wastewater streams must have specific compositions, otherwise the systems do not function appropriately. At the same time, said units such as urine separation toilets require a separate drainage system to be implemented in order to separate streams, which requires investments in infrastructure (Besson et al., 2021). This approach of separating waste/resource streams at the source has been a recent one which has not been implemented in many cities. Nevertheless, this challenge of avoiding contaminations of the input streams is critical to obtain well controlled systems of recovering and recirculate all components within the urban ecosystem and remains as the only effective solution to produce valuable resources without causing huge technological and financial challenges to minimize environmental and health risks.

Any NBS implementation plan in urban settings must also take into consideration the fact that, as previously described, there are limits to maintaining circular resource cycles within the cities. The greater population density of cities will always require some degree of resource importation from outside city boundaries. Solid material resources such as compost could be transported outside the city boundaries to provide nutrient resources to agricultural fields (Firmansyah et al., 2017). The output of these fields can later be transported inside the city. That way, the cycle does leave the city boundaries but maintains the necessary circularity. However, as long as the size of the market is sufficiently large to maintain specialized industries and to provide economically viable circular economy solutions, any kind of material can be recycled in the city-region boundaries (Zeller et al., 2019). It has been found that any type of waste with low market value accumulated at high density and high unit cost and transportation/treatment is more suited for local recycling (Zeller et al., 2019), which means urban wastewaters and organic waste are good sources to be used in urban ecosystems. Materials such as wastewater and solid waste, which are too voluminous and heavy and would require great energy expenditure to be feasibly exported back to rural areas, can in turn be used as source of nutrients to close the existing urban cycles (Wielemaker et al., 2019). The internal urban resource cycles which can be created by combining the several NBS and supporting units presented in this paper will therefore be of great use to reduce environmental impacts. Given their characteristics, NBS and supporting units can fill this niche to maintain the resource use and recovery in urban environments, first by compensating the flaws and limits of the dominant grey infrastructure, progressively replacing it entirely with natural systems, at different internal levels (household, district and citywide) (Langergraber et al., 2020), integrating nature into cities in a sustainable way.

The contributions each NBS unit can provide towards solving the circularity challenges present in cities are varied, and in combination, they can solve all technical challenges that have been defined in previous actions of the COST Action Circular City. The water cycle can be restored and maintained by treatment wetlands, algal photobioreactors, aerobic and anaerobic treatments, which treat wastewater and separate (micro)contaminants and materials and nutrients. Material and nutrient cycles in turn can be closed as NBS units such as insect farming, phytomining and composting upcycles them into products with added value, from protein-rich content for animal feed, to natural biofertilizers, to food products (thereby solving another of the technical challenges which had been found). In turn, most supporting units cannot solve the circularity challenges on their own, but it is their integration alongside the NBS units that can facilitate the closing of loops and connect the material and nutrient flows where there may be barriers. Here, complex (micro)contaminants such as pharmaceuticals and pathogens in wastewaters can be destroyed by disinfection processes such as UV, cavitation, or AOPs. Materials and nutrients particularly difficult to retrieve through purely biological processes can also be recovered by physical processing (e.g., membranes for wastewaters, ammonia striping), chemical processes (e.g., struvite precipitation) or thermal processing (biochar/hydrochar production). However, the efficient circularity of resources can be achieved only if cities implement urban farming or resources are used outside cities barriers. All of these potential solutions fulfil the objectives of achieving resource efficiency and circularity in cities set out by several institutions such as the European Union in their Green Deal (European Commission, 2019), their Action Plan for Zero Pollution for Air, Water and Soil (European Commission, 2021b) and ultimately their Circular Economy Action Plan (European Commission, 2020). Moreover, the 2030 Agenda for Sustainable Development set out by the United Nations can also be fulfilled with the closing of loops and waste reduction provided by the combination of NBS and Supporting Units, including the goals of Clean Water and Sanitation (SDG 6), Sustainable Cities and Communities (SDG 11), Responsible Production and Consumption (SDG 12) and Climate Action (SDG 13), among others (United Nations, 2015).

All the NBS and supporting units presented in this paper are proven systems (TRL > 5) with examples of application in urban areas. The great variety of solutions makes it feasible that connecting NBS and supporting units can form a circular network, in which all resources present in solid and liquid waste can therefore be reused, recovered and recycled. The analysis performed by Diaz-Elsayed et al. (2020) suggests that the life cycle impacts of resource recovery are generally decreased the higher the number of people served by them is, which means that by interlinking these units into larger scale systems overall environmental impact can be reduced even further. This fulfils the objective to reach a natural resource system within and/or associated to the city, achieving the objective of the Circular City. Nevertheless, the work of research and innovation in this field has continued, and in coming years new innovations and approaches are expected to continue to appear. By continually increasing reuse/recovery/recycling yields, the movement towards Circular Cities can continue to progress and provide natural solutions which improve urban ecosystems and provide human well-being and resilience towards climate change.

Conclusion

This paper attempted to provide an updated snapshot of the current characteristics and capabilities of nature-based solutions and supporting units based on physical and chemical processes. The data obtained enabled us to understand that, depending on the input and output of different systems, it is possible to create a network of technologies using mostly natural processes that can recover resources and reapply them in environmentally friendly ways. Limitations of many of these NBS can be overcome by integrating them into more complex but extensive systems with lower life cycle impact. This enables the development of solutions which are not only good from an environmental standpoint, but which are also economically and socially beneficial towards communities living in cities, improving their well-being and resilience towards the coming challenges of climate change.

The great variety of possible combinations between NBS and supporting units is a testament to their versatility, and their application is recommended in further projects and pilot tests throughout Europe and beyond. To that end, we recommend that future studies in the field of NBS focus on the study of circular networks to achieve new circular resource management units in cities, using not only the above-described proven systems (TRL > 5) but also other systems with lower TRL but with associated potential.

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Article

Nature-Based Solutions for Agriculture in Circular Cities: Challenges, Gaps, and Opportunities

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Abstract: Urban agriculture (UA) plays a key role in the circular metabolism of cities, as it can use water resources, nutrients, and other materials recovered from streams that currently leave the city as solid waste or as wastewater to produce new food and biomass. The ecosystem services of urban green spaces and infrastructures and the productivity of specific urban agricultural technologies have been discussed in literature. However, the understanding of input and output (I/O) streams of different nature-based solutions (NBS) is not yet sufficient to identify the challenges and opportunities they offer for strengthening circularity in UA. We propose a series of agriculture NBS, which, implemented in cities, would address circularity challenges in different urban spaces. To identify the challenges, gaps, and opportunities related to the enhancement of resources management of agriculture NBS, we evaluated NBS units, interventions, and supporting units, and analyzed I/O streams as links of urban circularity. A broader understanding of the food-related urban streams is important to recover resources and adapt the distribution system accordingly. As a result, we pinpointed the gaps that hinder the development of UA as a potential opportunity within the framework of the Circular City.

Keywords: urban agriculture; nutrient streams; urban food systems; urban circularity challenges; resources management; urban sustainability

1. Introduction

In the face of growing concerns about resource constraints and the need to act on the global climate emergency, many countries intend to move towards a greener, competitive, and "resourceful" urban circular economy (CE) [1–3]. Food and biomass production can significantly contribute to closing of material cycling, thus maximizing the reuse of resources in the urban environment itself while reducing the need for external resource inputs (I) [4–7]. The primary production of food and biomass within the city has environmental, social, and economic benefits depending on how the nature-based solutions (NBS) are implemented. The COST Action CA17133 Circular City "Implementing nature-based solutions for creating a resourceful circular city" (https://circular-city.eu) defines NBS as "concepts that bring nature into cities and those that are derived from nature. As such, within this definition, we achieve resource recovery using organisms (e.g., microbes, algae, plants, insects, and worms) as the principal agents. However, physical and chemical processes can be included for recovery of resources, as they may be needed for supporting and enhancing the performance of NBS" [6,8,9]. This definition is used as a reference concept in the present study.

1.1. Advantages and Challenges in the Contribution of Urban Agriculture towards Circularity in Cities

Placing food production in the city offers ample potential to improve the sustainability of the urban food systems. One aspect of urban placement is the shorter distance between food-production sites and consumers or stores, enabling faster delivery and reduction of storage capacity. Short food-supply chains are easier to supervise regarding quality and origin [10,11] and can contribute to food security [10,12]. They enable reduction of response reaction times to consumer demands and adaptation of cultivation programs to the needs of consumers [10]. Shortening distances decreases the use of fossil fuels in food transportation and, consequently, decreases the emissions of carbon dioxide [13], thereby contributing to climate change mitigation. Since these and other advantages/benefits—i.e., food security, economic, social, and environmental dimensions—of urban agriculture (UA) can lead to cleaner and more sustainable cities [4], it is important to consider the environmental impacts of any urban food production.

Introducing circular processes into the city offers opportunity to increase sustainability, and in this respect, Atanasova et al. [5] formulated a set of urban circularity challenges (UCC) [6,7]. Closing of the key cycles (i.e., water, nutrients, materials …) as much as possible [5–7,9] optimizes the utilization of urban resources [14,15]. Addressing the UCC_3 on "Nutrient recovery and reuse" [5] comprises areas of great concern in UA, e.g., nutrient streams—especially when phosphorous (P) is involved. Furthermore, issues arise concerning resilience and resource efficiency of urban food systems towards a CE approach: security and safety, transport and economic activities, food loss and waste management, and more, especially in relation to unexpected events and/or crisis, such as the COVID-19 pandemic and its lockdown measures [16].

If implemented to a high standard, UA can respond to several of the UCC [5–7], and it will cover a range of scales—from small scale, such as domestic food growing [17], to large scale, such as in peri-urban farming. Urban agriculture addresses primarily the UCC_5 of "Food and biomass production"; however, it touches on most other UCC as well [5–7]. Its primary production sites are located within the city boundaries or in transitional urban hinterland zones. Conceptual solutions for such zoning were already suggested in the nineteenth century by von Thünen in 1827 [18] and Howard in 1898 [19] in order to improve urban sustainability and further developed in the twenty-first century, e.g., within the Continuous Productive Urban Landscape concept [20].

Urban agriculture also requires a joint adaptation of other UCC within the urban-rural nexus, such as nutrient recovery and reuse (UCC_3), urban water management and treatment ($UCC_{1,2}$), and improved energy efficiency (UCC_6) [5–7]. The geographical locations, complex networks, and individual characteristics of each UA project— including its input (I) and output (O) resources—are of great importance for the project's success. However, for many sites and designs, only limited information is available about the type and interaction of food-focused NBS and their I/O streams, such as water or nutrients [7].

These missing site-resource inventories are one of the main gaps that prevent the circularity of UA. The present study aims to address this gap.

1.2. What Does Circularity Imply for Urban Agriculture?

According to the CE concept [9,21] cities can work towards three ambitions for a CE regarding food: (1) "sourcing food grown regeneratively and locally where appropriate", e.g., implementing circular urban farming systems, such as aquaponics [7,22,23]; (2) "making the most of food" by reducing food waste and/or transforming it into new products; and (3) "designing and marketing healthier food products", such as novel plant-based proteins, as alternatives to meat and dairy.

The current global food system has a notable environmental impact. Agriculture uses 85% of global water resources [24] and is responsible for about a quarter of all greenhouse gasses released by human activity. Food system analysis reveals that natural resource use and emissions associated with modern systems can be substantially reduced by shifting towards a circular system [25,26]. The aim is to reduce resource consumption and emissions to the environment, e.g., by closing the loop of materials. Moving towards a food system that sources and produces locally will prevent the leakage of elements, such as carbon (C), nitrogen (N), and phosphorous (P) and stimulate the reuse and recycling of resources in a way that adds value to the system [5,7].

According to de Boer and van Ittersum [27], circularity in agricultural production comprises three principles: (1) "plant biomass is the basic building block of food and should be used by humans first"; (2) "by-products from food production, processing, and consumption should be recycled back into the food system"; and (3) "use animals for what they are good at", i.e., from "low-opportunity-cost feeds" to valuable outputs and products.

While 10% of the world's population lives in hunger, a third of the food produced in the world is wasted every year, together with an increasing trend of population intensification [3,28]. Edible food surpluses can be redistributed, and products that are no longer edible could be turned into new products—from organic fertilizers to biomaterials, medicines, and bioenergy, thus boosting new sources of income in the bioeconomy [4,9,29,30].

The food production in a CE minimizes or eliminates waste, emulating natural processes in ecosystems where waste is transformed into resources that feed other processes. To be safely returned to the soil as compost or fertilizer, recovered resources must be free of contaminants. This implies separate treatment of waste streams to avoid cross-contamination [21,31]. The resulting cycles can contribute to the regeneration of ecosystems, which in turn provide renewable resources and support biodiversity. Investments in implementation and efficiency improvements are necessary for long-term success in the transition from linear to circular food systems [7,32].

1.3. The Objectives of this Study

The present study addresses the significance, roles, opportunities, and threats of UA within urban sustainability and climate resilience. It places UA as a key activity of any future city that decisively impacts on urban circularity measures and, at the same time, is itself impacted by urban circularity. Aiming to understand and make visible the necessary resource streams in relation to urban food, we discuss selected UA typologies in their complex interactions with other aspects of a circular city, namely the water, nutrient, material, waste, and building system cycles as well as energy flows [5–7].

Following the framework proposed by Langergraber et al. [6] to address UCC using NBS, this research aims to:

1. Evaluate NBS units (NBS_u), NBS interventions (NBS_i), and supporting units (S_u) addressing UCC on food and biomass production [6,33];
2. Define the input and output (I/O) streams, analyzing the inputs (I) necessary for the operation and the outputs (O) generated by UA related NBS (hereinafter UA-NBS);

3. Summarize the main circularity aspects that are relevant for UA; and
4. Pinpoint the gaps that currently hinder the efficient development and implementation of UA-NBS within the Circular City framework [8,9].

2. Materials and Methods

To answer the research questions above, four elicitation workshops with a multidisciplinary team of experts were held between January and April 2021 within the framework of the COST Action CA17133 Circular City. The workshops were based on the IDEA protocol, which stands for "Investigate", "Discuss", "Estimate", and "Aggregate" [34,35]. The workshops' participants were divided into four working groups (WG) formed within the COST Action Circular City and corresponding to the sectors of "Built Environment" (WG1); "Sustainable Urban Water Utilization" (WG2); "Resource Recovery" (WG3); and "Urban Farming" (WG4) [8,9]. The total number of participants in the Circular City workshops ranged from 70 to 81, and the UA expert group (WG4) was run by 6–11 members [7]. The WG4 comprised experts in agronomy, food science, urban planning and architecture, aquaponics systems, water-food-energy nexus, agricultural water management, participatory systems, and governance (further details can be found in Langergraber et al. [6,7]).

According to the methodology reported by Castellar et al. [33] and Langergraber et al. [6], the NBS were classified into NBS units (NBS_u), differentiating between spatial units (NBS_su) and technological units (NBS_tu), and NBS interventions (NBS_i), including soil interventions (NBS_is) and river interventions (NBS_ir), following the classification of Castellar et al. [33]. The list of NBS corresponded to that extended by Langergraber et al. [6], in which supporting units (S_u) were also considered to improve the functioning of the NBS. All these units addressed at least one UCC [5–7].

During the workshops, the following questions were posed to the UA expert group (i.e., WG4 members):

- How do the NBS_u, NBS_i, and S_u contribute to food and/or biomass production?
- Which NBS_u, NBS_i, and S_u are relevant to UA?
- How is food and biomass production (UCC_5) related to the other UCC?
- What are the main I/O streams of UA-NBS?
- What are the key opportunities and challenges for achieving circularity in UA?

2.1. Identification of Nature-Based Solutions Relevant for Urban Agriculture

The following steps were taken to identify the most relevant NBS regarding UA, i.e., selected from UA-NBS, and classify them according to the urban space in which they are located (implementation):

- Evaluation of food and biomass production (UCC_5): From a list of fifty-one NBS_u and NBS_i and ten S_u proposed by Langergraber et al. [6] and based on their contribution to the UCC_5 [5], a separate evaluation regarding food and/or biomass production was made for each NBS_u/i and S_u. To have a more accurate categorization adapted to the UCC_5, the rating was based on the relevance of either food or biomass inputs (I) or outputs (O) (Table 1). Thus, the proposed categories were as follows (Table 1):
    1. Food and/or biomass production with relevant I and/or O: UA-NBS whose main purpose is food and/or biomass production or that, due to its characteristics, produce a relevant amount of food and/or biomass and/or consume it for their operation;
    2. Usable for food and/or biomass production: UA-NBS that may produce food and/or biomass, even if it is not their primary purpose, contributing to the UCC_5; and

3. Food and/or biomass production with no relevant production levels: these UA-NBS can produce plant material or food in small quantities. They are considered as potential contributors that can be scaled up or designed for that purpose.

- Urban agriculture-related NBS-composed list: The NBS_u/i and S_u considered relevant for food and/or biomass production were those addressing, contributing, and/or potentially contributing to the food and/or biomass production (UCC_5).
- Classification according to typologies and urban space (implementation): The NBS_u/i related to UA were grouped according to the type of urban space they are associated with: (A) as urban blue infrastructure (urban water); (B) as green infrastructure (GI) in buildings (including containers); (C) as GI on buildings; (D) as GI for parks and landscape; and (E) as GI for the urban farm. NBS_u/i can be located in one or multiple urban spaces. The classification was based on the defining characteristics of the NBS, the expert knowledge of workshop participants, and literature references.
- Selection of representative UA-NBS: To narrow the list and focus on food and biomass production (UCC_5), eight UA-NBS were selected as relevant representatives to assess the I/O streams and identify circularity challenges. The selection was made according to the available references, considering that all typologies and urban spaces were covered, and upon the experience of the participants in the workshops. In order to gather information on the selected UA-NBS, a literature search was carried out using the names and synonyms given in Langergraber et al. [6].

Table 1. Marking system for urban circularity challenges (UCC) addressed by nature-based solutions units (NBS_u), interventions (NBS_i), and supporting units (S_u), following Langergraber et al. [6,7] and categorization used for food and biomass production (UCC_5).

Mark	General Category (UCC)	Food and Biomass Production Category (UCC_5)
●	Addresses directly the UCC	Food and/or biomass production with relevant I and/or O
● (grey)	Contributes to the UCC	Usable for food and/or biomass production
○	Contributes potentially depending on specific design	Food and/or biomass production with no relevant production

2.2. Linkages between Food and Biomass Production and other Urban Circularity Challenges

An evaluation of the NBS_u, NBS_i, and S_u in relation to the UCC was conducted to identify the existing gaps and opportunities to approach circular UA successfully based on the general assessment presented by Langergraber et al. [6]. The relationships revealed whether the UA-NBS implementation facilitates addressing other UCC, i.e., an opportunity, or whether it is a challenge to be considered.

2.3. Urban Agriculture-Related Nature-Based Solutions Circularity: Input and Output Streams

To identify the gaps in resource management within circular cities, I/O streams were defined using NBS_u, NBS_i, and S_u as CE entities, following the methodology defined by Baganz et al. [36]. General I/O streams were identified by all the WG participants from the COST Action Circular City based on an interdisciplinary approach [6], and the "Urban Farming" group (WG4) was focused on those streams directly related to UA. Following the framework proposed by Langergraber et al. [6], we used a systematic approach to describe in detail the resource streams (i.e., I/O streams) participating in the food and biomass production (the food system) by means of UA-NBS [36]. By using this approach, it was possible to determine the connection between the different sectors represented by the WG and food and biomass production for better resource optimization (Figure 1) [7].

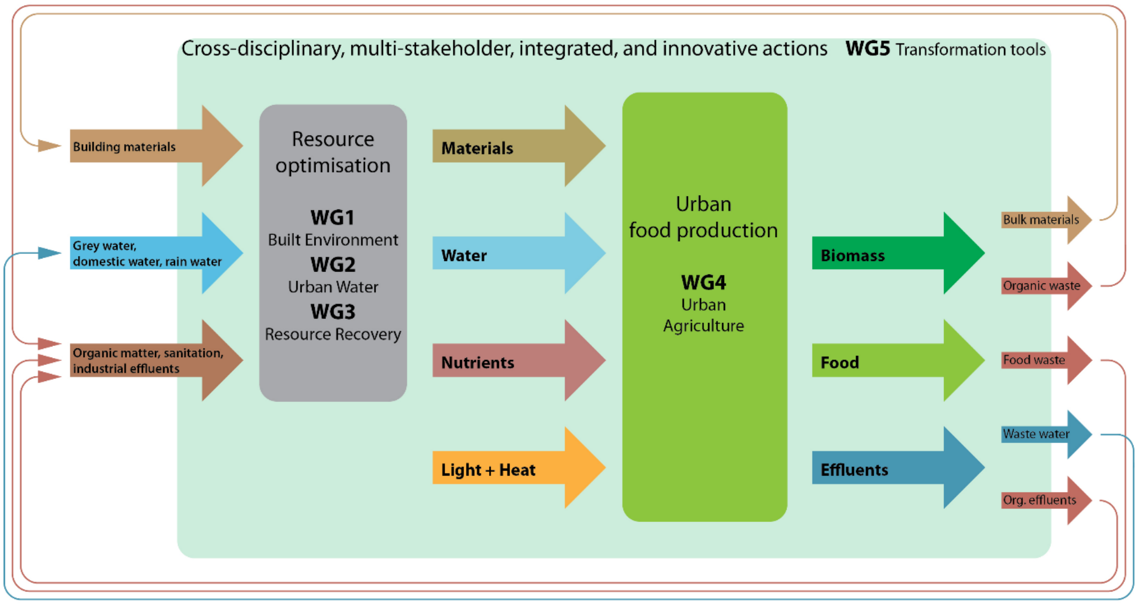

Figure 1. An urban agriculture centric view of the input and output streams studied within the working groups defined by the COST Action CA17133 Circular City on "Built Environment" (WG1), "Urban Water" (WG2), "Resource Recovery" (WG3), and "Urban Farming" (WG4) [7].

2.4. Identification of Key Challenges and Opportunities of Agricultural Nature-Based Solutions in Circular Cities

A SWOT analysis was used by the team of experts of "Urban Farming" (Working Group 4 of the COST Action) participating in the workshops to pinpoint internal (strengths and weaknesses) and external (opportunities and threats) factors influencing UA-NBS while addressing UCC, with particular attention to matter and energy flows as well as space, social, and economic effects.

3. Results and Discussion

3.1. Nature-Based Agricultural Solutions for Food and Biomass Production towards Urban Circularity

The fifth UCC proposed by Atanasova et al. [5] on "Food and biomass production" was rated separately both for food and for biomass production by using the methodology reported by [6] and, specifically for the UCC_5, following the criteria presented in Table 1, i.e., addressing the UCC_5, contribution to the UCC_5, and potential contribution, depending on specific design (see also Table 2 and Figure 2). Those UA-NBS not addressing the UCC_5 (i.e., without food and/or biomass production) are not presented in Table 2 for not being considered within the objectives of this study (related details can be found in Langergraber et al. [7]).

Table 2. Selected urban agriculture related NBS units and interventions (UA-NBS_u/i) and supporting units (UA-S_u), addressing the fifth urban circularity challenge on "Food and biomass production" (UCC_5) [5,6]: ● addressing the UCC_5 by food production, biomass production, and food and biomass production (score = 1.00); • contribution and o potential contribution to the UCC_5 depending on specific design (scores = 0.66 and 0.33, respectively). Empty cells are those UA-NBS_u/i and UA-S_u not addressing the UCC_5 via food or biomass production.

Classification [1,2]	(#) UA-NBS_u/i and UA-S_u [3]	Food	Biomass	UCC_5	Implementation [4]
• NBS_tu	(1) Infiltration basin		○	○	A
	(5) (Wet) Retention pond		○	○	A
	(7) Bioretention cell		○	○	A
	(8) Bioswale		○	○	A
	(9) Dry swale		○	○	A
	(10) Tree pits	○	○	○	A,D
	(11) Vegetated grid pavement		○	○	A,D
	(12) Riparian buffer		•	•	A
• NBS_tu	(13) Ground-based green facade	•	•	•	B,C
	(14) Wall-based green facade	•	•	•	B,C
	(15) Pot-based green facade	•	•	•	B,C
	(16) Vegetated pergola	•	•	•	B,C
	(17) Extensive green roof	•	•	•	C,D
	(18) Intensive green roof	•	●	●	C,D,E
	(19) Semi-intensive green roof	•	●	●	C,D
	(20) Mobile green and vertical mobile garden	•	•	•	B,C
• NBS_tu	(21) Treatment wetland		•	•	A,D
NBS_is	(23) Composting	•	●	●	C,E
	(25) Phytoremediation		•	•	B,C
S_u	(S6) Biochar/Hydrochar production		●	●	—
	(S7) Physical unit operations for solid/liquid separation		•	•	—
	(S11) Chemical and biological methods		•	•	—
• NBS_ir	(28) River restoration		•	•	A,D
	(29) Floodplain		•	•	A,D
	(32) Coastal erosion control	○		○	A,D
• NBS_is	(33) Soil improvement and conservation	○	•	•	D,E
	(34) Erosion control		○	○	D,E
	(36) Riverbank engineering		○	○	A,D
• NBS_su	(37) Green corridors	○	•	•	D,E
	(38) Green belt	○	•	•	A,D
	(39) Street trees	•	•	•	D
	(40) Large urban park	•	•	•	D,E
	(41) Pocket/garden park	•	•	•	D,E
	(42) Urban meadows	○	•	•	D
	(43) Green transition zones	○	•	•	D
• NBS_tu	(44) Aquaculture	●	○	●	A
	(45) Hydroponic and soilless technologies	●	•	●	A,B,C,E
	(46) Organoponic/Bioponic	●	•	●	A,B,C,E
	(47) Aquaponic farming	●	•	●	A,B,C,E
	(48) Photo Bio Reactor		●	●	B,C
NBS_su	(49) Productive garden	●	●	●	D,E
	(50) Urban forest	•	●	●	D
	(51) Urban farms and orchards	●	●	●	D,E

[1] • Rainwater Management, • Vertical Greening Systems and Green Roofs, • Remediation, Treatment, and Recovery, • (River) Restoration, • Soil and Water Bioengineering, • (Public) Green Space, • Food and Biomass Production, following color legend presented at Langergraber et al. [6,7]. [2] NBS_tu, nature-based solution technological unit; NBS_is, soil intervention; S_u, supporting unit; NBS_ir, river intervention; NBS_su, spatial unit [6,7]. [3] Numbered (#) according to Langergraber et al. [6,7]. [4] Typology and urban space where the rated UA-NBS_u/i would be implemented: (A) as urban blue infrastructure; (B) as green infrastructure (GI) in buildings; (C) as GI on buildings; (D) as GI for parks and landscape; and (E) as GI for the urban farm.

In total, 43 UA-NBS (i.e., 40 NBS_u/i and 3 S_u) were selected to address UCC_5 as those implemented/designed to produce food and/or biomass; the match between food and biomass production was the final rate addressing UCC_5 (Table 2, Figures 2 and S1). We propose a S_u on Chemical and biological methods (S11) to be considered as addressing UCC5, since it was not previously reported in the framework proposed by Langergraber et al. [6]. This S_u would include those enzymatic and fermentation processes involving UCC_5—mainly biomass production/transformation [37] (Table 2).

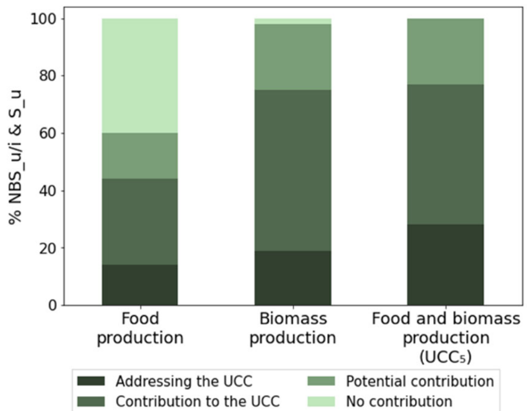

Figure 2. Colum chart representing the selected 43 NBS_u/i and S_u and categorized as those addressing, contributing, and potentially contributing to the UCC_5 on "Food and biomass production", respectively.

The selected UA-NBS_u/i and S_u were grouped within the three main groups presented in Table 1 as those categorized as follows: (1) Food and/or biomass production with relevant I and/or O, addressing the UCC_5-11 NBS_u/i and 1 S_u; (2) usable for food and/or biomass production, contribution to the UCC_5-19 NBS_u/i and 2 S_u; and (3) food and/or biomass production with no relevant production, representing potential contribution depending on specific design-10 NBS_u/i (cf. Tables 1 and 2, Figure 2) [6,7]. The later classification refers to those NBS_u/i intrinsically composed of vegetation and not primary designed for food and/or biomass production as the ones categorized for "Rainwater Management" [6,7]. However, the actions and infrastructures would be designed and implemented as food and/or biomass systems and technologies [7].

A second classification concerns to the implementation of the relevant UA-NBS_u/i and S_u according to their typology and typical urban site (Table 2). In this sense, 18 NBS_u/i were classified as urban blue infrastructure (A); 10 as green infrastructure (GI) in buildings (B); 14 as GI on buildings (C); 22 as GI for parks and landscape (D); and 12 specifically for GI as urban farms (E). Pearlmutter et al. [38] presented the state of the art on NBS in the built urban environment as the level of green building materials, systems, and sites [3]. Similarly, some of the selected UA-NBS_u/i and S_u presented in this study are classified following two of the three scales of described NBS implementation in the built environment by Pearlmutter et al. [38] at green building systems (i.e., in/on buildings' greening) and sites (e.g., parks and landscape and urban farms).

3.2. Relevance of Nature-Based Solutions Related to Urban Agriculture to Address the Fifth Urban Circularity Challenge

We highlighted and analyzed eight UA-NBS_u (*NBS_tu* and *NBS_su*) from the previously selected group of 40 units and interventions indicated in Section 3.1 as relevant representatives regarding the UCC_5 [6,7]. Among them, two belonged to the category of "Vertical Greening System & Green Roofs": wall-based green facade (14) and intensive green roof (18); one to the "(Public) Green Space" category: green corridors (37); and five to the "Food and Biomass Production" classification: hydroponic and soilless technologies

(45), organoponic/bioponic (46), aquaponic farming (47), productive garden (49), and urban farms and orchards (51) (Table 2, Figure S1). The selected representatives UA-NBS_u, were clustered as both general categories on addressing and contribution to the UCC_5, with food and/or biomass production with relevant I/O and as usable for food and biomass production, respectively (Table 2, Figure S1).

Particular attention was given to describe their main characteristics and capacity for food and/or biomass production, with an emphasis on their contribution to circularity in cities, identifying potential I/O streams, and how they relate to the city's resource flows (cf. Sections 3.3–3.5):

1. Wall-based green facade (14): Wall-based green facades, as "Vertical Greening Systems", are known for their ability to mitigate urban heat island (UHI) effect and to enhance building energy savings in the urban environment, e.g., increasingly, the possibilities for crop production and wastewater treatment, particularly greywater [39–41]. They mostly consist of a modular vertical support structure with vegetation, substrate, irrigation, and drainage systems. Depending on the purpose of the system, different plants are used, with low-maintenance plants being the most common option to minimize costs. This NBS_tu can produce ornamental plants (low maintenance) as well as horticultural crops. When designed for food production, they are generally used for self-consumption and local supply (e.g., restaurants, schools, or hospitals) [42]. The yield depends on the crop/plant, type of substrate, management, irrigation and drainage systems, and the climate and orientation when it is placed outdoors. Indoor, wall-based green facades under controlled conditions at buildings or greenhouses are mostly used to produce high-yielding crops. In order to address circularity, it is relevant to characterize drainage water, which can be reused since it is rich in nutrients. Additionally, wall-based green facades can be designed as modular treatment systems when irrigated with wastewater, resembling constructed wetlands, where plant matter can be harvested and used as biomass [39,43].
2. Intensive green roof (18): Green roofs can be used to cultivate agricultural products, and their importance for this purpose has increased in recent years, as they provide additional land space in urban centers [44,45]. Intensive green roofs are characterized by a substrate depth between 15 and 70 cm, which requires more maintenance than extensive ones and allows for a wider choice of plants [46]. As an engineered structure, a green roof requires prefabricated materials to be constructed, such as protection and drainage layers, substrate, etc. Such structures may be built in residential buildings but also in commercial ones. For example, a supermarket in Brussels, Belgium (Delhaize chain), has a 360 m^2 urban farm on the rooftop for greenhouse and open-air vegetables, with a certified organic production system [47]. The aim is to control the production system and sell the products in the supermarket on the ground floor, avoiding transportation and the need for a cold chain. The residual heat from the refrigeration systems is used to heat the greenhouse, improving energy efficiency (UCC_6). Since the farm is small, and the impact is thus limited, it serves as a demonstrator of possibilities for professional UA.
3. Green corridors (37): According to Castellar et al. [33], green corridors aim to re-naturalize areas along derelict infrastructure, such as railways or along waterways and rivers, by transforming them into linear parks. Green corridors can play an important role in urban GI networks and can offer shelter, food, and protection for the urban wildlife while enabling migration from one green patch to another. Back-up irrigation may be provided by reclaimed wastewater, and the biomass produced can be used for energy generation and composting. As for the vegetation planted, it depends on the site and the objectives set. Forest species, fruit trees, and fruiting shrubs or ornamental species are generally used. Lisbon (European Green Capital 2020) is an example of a network of nine green corridors that are part of the urban GI. They cover an area of about 200 ha and contribute to ecological connectivity, create spaces for UA, revalorize abandoned spaces by increasing soil permeability, and improve the

connection to other NBS specialized in rainwater retention and infiltration [48]. Other cities, such as Montreal, Mexico City, Seoul, London, or Singapore, also have green corridors that provide ecosystem services to the city [49]. At each site, this NBS_su is adapted to the local context, from the use of plant species and the reuse of the available resources to the using of space according to social needs.

4. Hydroponic and soilless technologies (45): In hydroponics, plants grow in water containing necessary macro- and micronutrients that are supplied by mineral fertilizers dissolved in water according to the plant-specific recipe. In ebb and flow systems and in grow beds, the plants grow in different media, like mineral-/rockwool, vermiculite, sand, gravel, etc., which also offer mechanical support [4,50,51]. Other soilless technologies, such as nutrient film technique, aeroponics, and deep flow technique, do not involve media. Recently, soilless technologies are being innovated by implementing artificial intelligence to learn the best way of composition of synthetic, mineral, or organic fertilizers to grow the crop, often together with artificial light in greenhouses or plant factories.
5. Organoponic/Bioponics (46): In contrast to hydroponic that relies on mineral fertilizers, bioponics is an emerging soilless technology for nutrients recovery that links (organic) vegetable production to organic effluent remediation or organic waste recycling [52]. The plants in growing media derive nutrients from natural animal, plant, and mineral substances that are released by the biological activity of microorganisms [53]. Bioponics allows closing nutrient cycles by using organic waste streams, such as urine [54], biogas digestate [55], chicken manure [52,56], and others, thus reducing the use of mineral fertilizers and the greenhouse gas emissions. Aquaponics [57] could also be considered as a form of bioponics, as it utilizes waste streams (process water, sludge) from an aquaculture. Synonyms used for bioponics are "organic hydroponic" [58,59], digeponics [60], or anthroponics [61]. Beside the source of nutrients, the key difference between organic and conventional soilless culture is the active promotion of microorganisms in bioponics to enhance nitrification, mineralization, and disease suppression and thus contribute to productivity and plant quality similar to soil-based systems [62].
6. Aquaponic farming (47): Aquaponics is a technology that couples tank-based animal aquaculture with hydroponics by using water from aquaculture for plant nutrition and irrigation. Trans-aquaponics extends this technology to tankless aquaculture and/or non-hydroponic plant cultivation. Aquaponic farming comprises both aquaponic types, whereby aquaponic farming does not imply a specific size but the fact that such this generic NBS_tu can embody both aquaponics types [22]. The NBS_tu can be established in very different setups: while aquaponics is often implemented as controlled environment agriculture, trans-aquaponics includes, e.g., pond-aquaponics [63,64], outdoor aquaponics [65,66], aquaculture using constructed wetland for sludge removal [22], and other integrated aqua-agriculture systems [67] that exploit the aquaponics principle. Both technologies are often used for food production, but aquaponics cannot be eco-certified because it exploits hydroponics and is thus not soil-based, a precondition for eco-certification—at least in the European Union. However, it is possible to meet a large city's demand for tomatoes, fish, and lettuce through aquaponic production, as shown in a case study related to Berlin [23].
7. Productive garden (49): Productive gardens are found around the world and contribute significantly to food security. Vegetables, fruits, herbs, and, occasionally, small livestock are produced in reduced spaces for the market, private consumption, or educational purposes. The productivity of urban gardens depends on climate conditions and type of crops and can exceed that of rural farms [68]; if correct cultures are selected and machine-based crop treatment technologies are replaced by manual work, it results in higher cropping density and higher biodiversity of crops to be grown together [69]. Different types of cultivation can be selected for horticultural crops, both in open fields and/or under cover.

8. Urban farms and orchards (51): Urban farms and orchards are part of the city's GI and are intended for food and biomass production. They are large enough to grow cereal crops, fruit and vegetables, and even big livestock [6]. This NBS_su can seek an economic profit or have social and educational purposes. It is common to find urban farms located in public areas and managed by a community (e.g., neighborhood). While other NBS_u are more specific, with a defined configuration, this unit encompasses a wide range of possibilities that make it very versatile. It is the NBS_su that most resembles the rural farms, with the advantage of having the urban streams nearby to tap into. For example, food waste—which has a high nutritional value—can be used to feed animals and lower the production costs; on the other hand, treated water can be used for irrigation [27]. Within its boundaries, several other NBS can be implemented to close loops, such as composting (23) or constructed wetlands for wastewater or runoff water treatment for on-farm resource recovery and reuse.

Once the selected UA-NBS_u were analyzed individually, we compared their joint contributions to the UCC_5 (cf. Figure 3). Their contribution to food and biomass production, as defined in Table 1, resulted in scores of 1.00 (●), 0.66 (●), and 0.33 (○), corresponding to each representative NBS_u (cf. Table 2, Figure S1). Some UA-NBS_u have an important share in both food and biomass production, as is the case of productive garden (49) and urban farms and orchards (51). Other UA-NBS_u were specifically designed for food production, so the contribution to food production is higher than that of biomass, as in the case of hydroponic and soilless technologies (45), organoponic/bioponic (46), and aquaponic farming (47). However, they can also be used for biomass production [7]. In contrast, green corridors (37) generally produce large amounts of biomass; however, the capacity to produce food is lower, generally attributed to berries and fruits from trees and shrubs. If designed to include production sites (e.g., productive gardens) or specific plants, they can contribute to food production. A wall-based green facade (14) can also produce food and biomass, although its main purpose is often UHI mitigation and building energy savings. Finally, an intensive green roof (18) encompasses different types of herbaceous and shrub species, including trees, producing biomass; however, it can also contribute to food production.

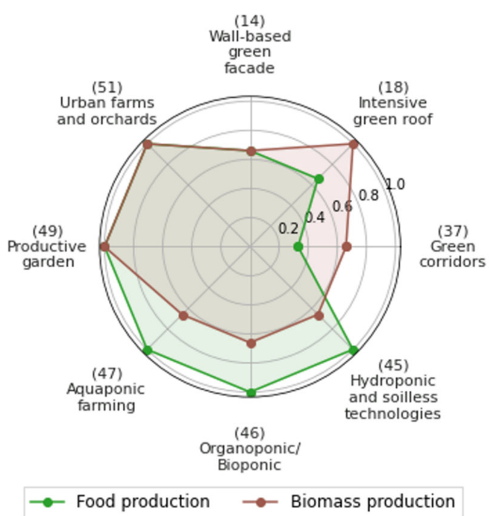

Figure 3. Evaluation for food and biomass production of nature-based agricultural solutions selected as urban agriculture representatives. Numbers of technological and spatial units (NBS_tu and NBS_su) corresponds to that given by Langergraber et al. [6] (cf. Table 2).

3.3. Interfaces between Food and Biomass Production and the other Six Urban Circularity Challenges

The UCC on "Food and biomass production" (UCC_5) [5] seeks to close the production loop, maximizing the use of available resources while reducing the need for external resource inputs. The UA-NBS_u addressing the UCC_5 are closely related to other UCC [5–7]. Urban food production faces challenges, such as nutrient and water supply, urban planning, and energy efficiency. Conversely, the urban environment also offers opportunities for farming different to those in rural environments. Figure 4 indicates whether the implementation of UA-NBS is an opportunity to address other UCC or whether an UCC poses a challenge for food and biomass production in order to close material loops, improve energy efficiency, and make use of urban spaces.

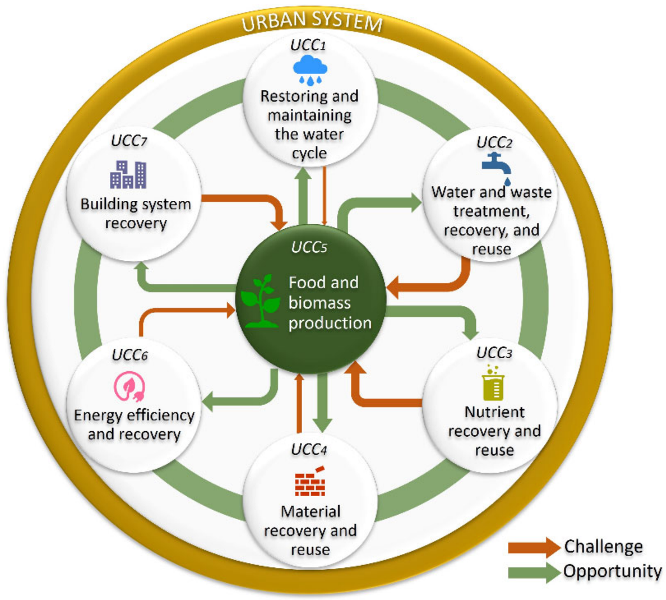

Figure 4. Relationships among food and biomass production and other urban circularity challenges described by Atanasova et al. [5–7]. The thickness of the arrows indicates the relevance of the opportunity or challenge, respectively. UCC: (**1**) Restoring and maintaining the water cycle (by rainwater management); (**2**) water and waste treatment, recovery, and reuse; (**3**) nutrient recovery and reuse; (**4**) material recovery and reuse; (**5**) food and biomass production; (**6**) energy efficiency and recovery; and (**7**) building system recovery [5].

(1) "Restoring and maintaining the water cycle (by rainwater management)"—UCC_1: Several NBS_u/i and S_u identified as relevant for the UCC_5 also address the UCC_1. The nature of the NBS_u/i, with a significant vegetation component and located in different urban spaces, such as the UA-NBS classified as "Vertical Greening Systems and Green Roofs" and "(Public) Green Space"—e.g., green corridors (37) and large urban parks (40) —, enable the restoration and maintenance of the water cycle at different scales. These NBS_u/i facilitate processes, such as water retention, infiltration, transport, treatment, and evapotranspiration [70]. The UA-NBS_su from the category of "Food and Biomass Production", i.e., productive garden (49), urban forest (50), and urban farms and orchards (51), are also relevant for the UCC_1, as they enable the same processes as the above. The implementation of these UA-NBS_u is seen as an opportunity to regulate the water cycle and not a barrier to be overcome in the sector of UA.

(2) "Water and waste treatment, recovery, and reuse"—UCC_2: NBS_u/i and S_u addressing the UCC_2 are crucial for UA, as water is a continuous input stream to most UA-NBS. In general, a minimum quality is required to use reclaimed water for irrigation and fertigation. In addition, some UA-NBS may require a certain quality depending on the crop or culture. Furthermore, the effluent water from UA-NBS, e.g., aquaculture (44) and photo bio reactor (48), needs to be treated, and for this purpose, other

NBS_u/i and/or S_u, such as circular systems like aquaponic farming (47), can be implemented [71].

(3) "Nutrient recovery and reuse"—UCC3: Nutrient recovery, reuse, and recycling is key to achieving a circular metabolism of cities [31,72]. For this purpose, it is necessary to identify and analyze the nutrient-rich flows generated in the city, such as wastewater or organic waste. Urban agriculture harnesses the recovered nutrients and keeps them in the urban system. Besides, the NBS_u and S_u from the category of "Remediation, Treatment and Recovery" [6,7] (cf. Table 2) comprise anaerobic treatment (26), phosphate precipitation (for P recovery) (S3), and ammonia stripping (for N recovery) (S4), and they are not considered as relevant for food and biomass production because they do not generate food and/or biomass to a significant extent nor require it to operate. However, they may be crucial for nutrient recovery from urban streams to be used in UA-NBS. In addition, the recovered nutrients must be able to meet the needs of crops or living organisms, considering the macro- and micronutrients required for production. It is therefore seen as both a challenge and an opportunity to recover and reuse nutrients.

(4) "Material recovery and reuse"—UCC4: Material recovery is seen as an opportunity for UA. Urban agriculture can provide a considerable amount of biomass that can be used for several purposes, e.g., building materials, soil amendment, or energy production. For example, biochar/hydrochar production (S6) and composting (23), classified as S_u and NBS_is, respectively ("Remediation, Treatment and Recovery"), can be obtained from the biomass produced in vertical greening systems and agricultural waste. Biodegradable materials, such as wood, can be used directly to build structures. One challenge would be to replace stable insulating materials, such as plastic and glass, or materials used in irrigation pipes. This could be accomplished by using recovered and/or recycled materials.

(5) "Energy efficiency and recovery"—UCC6: Mitigation of UHI effect is one of the strengths of UA-NBS in urban outdoor spaces such as infrastructure, i.e., NBS_u/i and S_u located in/on buildings, in parks and landscape, and/or urban farms. At the building scale, green roofs or vertical greening systems can improve energy efficiency by reducing rooftop and walls' surface temperature during summer, improving insulation and decreasing heat losses during the cold season [42]. On the other hand, NBS_u that include greenhouses or are located indoors may require energy to regulate room temperature and to provide artificial lighting. However, high-yield crops or indoor urban vertical farming using hydroponics and soilless technologies (45) can substantially increase energy efficiency [73,74]. In addition, within the urban system, there is the possibility of recovering heat sources for food and biomass production that would otherwise be lost.

(6) "Building system recovery"—UCC7: An urban system is multi-stakeholder and space-constrained; therefore, the essential planning to achieve circularity is challenging. Both the design of new spaces and the retrofitting and adaptation of old ones require planning for the effective implementation of the NBS_u/i. By using UA-NBS, urban spaces can be revalorized, although the complexity of the urban system makes it a challenge for food and biomass production, as there are different ownerships, available spaces, and regulations to consider. Achieving circularity may require new approaches.

3.4. Contribution of Input and Output Streams to Urban Circularity in Nature-Based Agricultural Solutions

From a CE perspective, UA is seen as an opportunity to counteract the linear "take-make-waste" economy [16]. Urban agriculture can be designed to minimize the need for external inputs to produce food and biomass to be consumed in the city. This emerging and inclusive approach consists of making the most of the materials and waste streams used for production, closing water and nutrient loops, and reducing discharges into the environment [7,16,75]. In this sense, circularity refers to the connection between urban streams and the streams needed in UA. From the standpoint of the NBS_u/i and S_u, an urban stream of matter or energy with the appropriate characteristics becomes an input stream. In turn, the output stream of one NBS_u/i or S_u can become the input stream of another, thus tapping into urban resources. Based on system analyses of resource streams and a corresponding streams information model to describe inputs and outputs (I/O) [7], a practical solution to enhance circularity by concrete streams is presented (Table 3, Figure S2).

Table 3. Biomass and living organisms as resource streams related to nature-based solutions units (NBS_u) associated with urban agriculture while address the fifth urban circularity challenge on "Food and biomass production" [5–7].

<table>
<tr><th>Stream Type</th><th>Category</th><th>Subcategory</th><th>I in UA-NBS_u [1]</th><th>O from UA-NBS_u [1]</th></tr>
<tr><td rowspan="5">Biomass</td><td>Organic fertilizer</td><td>Compost
Manure (types)</td><td colspan="2">(18) (37) (49) (51) [2]</td></tr>
<tr><td>Organic crop protection</td><td>Mulch
Woodchips
Biochar</td><td colspan="2">(18) (37) (49) (51)</td></tr>
<tr><td>Food waste</td><td>Vegetables, fruits</td><td>—</td><td>(18) (37) (49) (51)</td></tr>
<tr><td>Crop residues</td><td rowspan="2"></td><td rowspan="2">(18) (37) (49) (51)</td><td>(14) (18) (37) (45) (46) (47) (49) (51)</td></tr>
<tr><td>Pruning remains</td><td>(14) (18) (37) (49) (51)</td></tr>
<tr><td rowspan="13">Living organisms</td><td>Plants</td><td>Edible
Ornamental
Seedlings</td><td colspan="2">(14) (18) (37) (45) (46) (47) (49) (51)</td></tr>
<tr><td>Algae</td><td></td><td colspan="2">(45) (46) (47)</td></tr>
<tr><td rowspan="2">Fish</td><td>Marketable</td><td>—</td><td>(47)</td></tr>
<tr><td>Fingerlings</td><td colspan="2">(47)</td></tr>
<tr><td>Poultry</td><td></td><td colspan="2">(18) (37) (49) (51)</td></tr>
<tr><td>Livestock</td><td></td><td colspan="2">(37) (49) (51)</td></tr>
<tr><td rowspan="2">Worms</td><td>Edible</td><td colspan="2">(51)</td></tr>
<tr><td>Other</td><td colspan="2">(18) (37) (49) (51)</td></tr>
<tr><td rowspan="3">Insects</td><td>Edible</td><td colspan="2">(51)</td></tr>
<tr><td>Auxiliary</td><td colspan="2">(14) (18) (37) (45) (46) (47) (49) (51)</td></tr>
<tr><td>Aquatic, larvae</td><td colspan="2">(47)</td></tr>
<tr><td>Mushrooms</td><td></td><td colspan="2">(51)</td></tr>
<tr><td>Microorganisms</td><td>Mycorrhiza, Bacteria
Fungi
Aquatic</td><td colspan="2">(18) (37) (47) (49) (51)
(18) (37) (49) (51)
(47)</td></tr>
</table>

[1] I: input to NBS_u, required for its operation and maintenance; and O: output from NBS_u. [2] (#): number assigned according to Table 2 [6,7].

According to Langergraber et al. [6], the main types of input and/or output streams of UA-NBS were analyzed following the categories below:

- Biomass and Living organisms (cf. Table 3): Biomass refers to the total mass of all living organisms in an area. In a circular city, that means all organic materials derived from produced plant mass together with all microorganism and animals, important in a CE point of view [76]. Biomass is an important resource for technologies like pyrolysis—conversion of biomass to biochar—heat transfer [77], Fe2/biocarbon composite derived from a phosphorous-containing biomass [78], and several other biomass-derivate methods. Biomass concerns to materials including soil conditioners, such as wood chips or biochar; organic fertilizers, such as manure or compost; different types of organic waste, ranging from food waste to crop residues or pruning residues; and to organic crop-protection products (Table 3, Figure S2). Cultivation of plants, mushrooms, and insects may positively influence the air and soil quality. Plants take up essential nutrients from the soil; however, they can also absorb metals like lead (Pb), cadmium (Cd), arsenic (As), tin (Sn), chromium (Cr), and nickel (Ni). This makes certain plants, together with other living organisms, effective phytoremediators [79].

- Water: Irrigation water is required whenever precipitation is not sufficient. Using tap water may lead to competition with other urban users [80]; therefore, alternative water sources should be preferred. These could be subterranean water, stored rainfall water, or treated wastewater. Urban agriculture provides an opportunity to reuse (waste)water wherever it is generated, as opposed to rural agriculture, because there are no or less costs associated with transport. The use of water is minimized in soil-independent production systems with a closed circuit for water, as exemplified by Rufí-Salís et al. [14], who found daily water savings up to 40% for such systems. However, soilless systems mostly require higher energy inputs [81].
- Nutrients: Nutrient-rich urban waste for the primary production can be recycled from wastewaters of different provenance, e.g., domestic wastewater, urine, feces, greywater; wastewaters from food production, e.g., milk, tea, coffee, brewery; and nutrient-rich solid waste streams, e.g., composting, biogas, biochar. The nutrient-rich streams usually need to be subjected to one or several stages of treatment before use in UA. As Jurgilevich et al. [82] pointed out, the demand for nutrients, especially phosphorous (P), is growing drastically faster than the human population. This is coupled to large nutrient losses on one side [83] and increasing global nutrient imbalance [82] on the other. While the soils of rich countries accumulate nutrients, the soil in developing countries experience P deficit [84]. Schoumans et al. [84] argued that the European P cycle could be completely closed if imported chemical P fertilizers were replaced by P fertilizers recovered from waste streams.
- Energy: Energy flows can be optimized, too. Mohareb et al. [85] proposed co-location strategies of agricultural operations and waste streams in order to increase energy efficiency; this is the sixth urban circularity challenge (UCC_6) proposed by Atanasova et al. [5] on "Energy efficiency and recovery" that is mainly addressed. Such a strategy can be, for instance, to locate greenhouse food production next to waste heat or waste nutrient sources, such as from biogas or refrigeration equipment. Another possibility would be using phase-change technologies [86] to mediate between the locations that emit waste heat and locations that require heat, therefore obliterating the need for close proximity of these operations.

Urban agriculture must adapt the field agronomic production methods to smaller areas in urban spaces, as the available surface is restricted. Therefore, crop production in the urban environment tends to intensify in the direction of high edible biomass per surface unit, e.g., green leafy vegetables, legumes, using plants with short life cycle; therefore, annuals are preferred over fruit trees [87]. This intensification optimizes the use of soil, while soil-independent systems, either horizontal or vertical, further enable increased production rates per area. This is the case of hydroponics or aquaponic systems, where multilayer or multilevel systems can be used to enlarge cultivation surface. However, soil-based UA is more adequate for nutrient recycling, as the most used method for this process is the composting of solid organic waste [88]. The substrate to use in UA might be soil resulting from a natural process or fabricated, sometimes recurring to waste as main structural components or just as amendments from different urban waste streams [89]. Soils previously occupied with industrial facilities may have elevated toxicity levels, but several techniques can be used to overcome this problem [89,90].

3.5. Challenges of Circular City Resource Flows

The current research highlights the role of resource streams to close loops within the urban metabolism, thus creating a Circular City [4–7,36]. For two types of resource streams (i.e., food and biomass production) stream categories are shown in Table 3. Each stream is attributed as output (O) from and/or input (I) to appropriate NBS units (NBS_u); other non-NBS-endpoints, such as biogas plants, private gardens, or the "market", are also possible. With this qualitative representation, a part of a Circular City resource network could already be constructed. However, the challenges should not be underestimated, as both the qualitative and quantitative properties of the NBS_u must be matched. A good example to demonstrate possible difficulties with Circular City resource flows is NBS_u aquaponic farming (47) [6,7].

Aquaponic farming can be configured very differently internally and thus integrated flexibly within the Circular City, but that impacts input (I) resource demands and output (O) resource provisions significantly. For example, an aquaponic system that uses a combined heat and power unit may produce electrical energy instead of consuming it. Another example is the externalization of the most important internal resource stream, the transfer water, that cannot optimally supply the hydroponics. It requires targeting of the plant needs by the addition of fertilizer depending on the fish species, stocking density, and plant species [91,92]. This can be controlled since aquaculture and hydroponics are operated jointly by one operator. If aquaponic elements are split into separate units as distinct NBS with potentially different owners or operators [36], this coordination process becomes more difficult. Additionally, in extended aquaponics, the plants may grow in soil rather than hydroponically, involving another nutrient source to be considered. This concerns the qualitative side of the material flow, but the quantitative aspects of coupling can also pose problems. For example, young tomato plants need considerably less water than mature plants, but aquaculture provides a constant fish-water output. This mismatch can be countered with staggered crop production, which in turn requires a greenhouse and year-round operation [93].

But even if these problems are solved, there is still the site question, and the proposal to use the roofscape must be critically questioned due to the prevailing usage competition in cities.

3.6. SWOT Analysis of Urban Agriculture Related Nature-Based Solutions

A SWOT analysis was used to determine the strengths, weaknesses, opportunities, and threats of UA-NBS implementing the UCC_5 in practice (cf. Figure 5). Internal factors are attributes of the UA-NBS that represent either a strength or a weakness, and they depend on the objective to be achieved, in this case, addressing the UCC_5. Opportunities and threats are external factors that depend on the studied context, i.e., an urban environment with great potential for resources recovery due to the large volume of waste and wastewater generated.

- Strengths of UA are the reduction of the environmental footprint by using sustainable production methods, enabling organic certification, and increasing profitability [94] (Figure 5).
- Weaknesses identified in UA-NBS are the lack of professional experience that can lead to inappropriate use of phytosanitary products, thus aggravating pollution problems in the city. In addition, the risk of contamination is higher when treated water or materials obtained from waste are used instead of sources, such as mainstream water or freshwater. Traceability of products by means of regular monitoring and digital tools, e.g., internet of things (IoT) and blockchain technology (BCT), would facilitate both food safety and environmental risk mitigation (Figure 5).
- Opportunities include that the implementing UA-NBS as part of a sustainable bioeconomy in cities facilitates the reuse of resources stemming from urban metabolism, e.g., building materials, water, and nutrients reduce the environmental footprint of

the final products [95]. For this purpose, Langergraber et al. [6,7] proposed supporting units that enable nutrients and carbon to be recovered and directed back into the system. In this regard, regulations like the recently approved European Union Circular Economy Fertilizing Products Regulation (EU 2019/1009) may facilitate the use of fertilizers that are produced in the same city, fostering circularity. Urban metabolism and industrial synergy provide multiple streams of different characteristics that can be harnessed for food and biomass production.

- Threats are, as noted above, the mismatch between the supply of nutrients and tracer elements recovered from wastewater and waste streams and the nutritional demand of crops, which can create a surplus or a deficiency [31,72], which has to be considered.

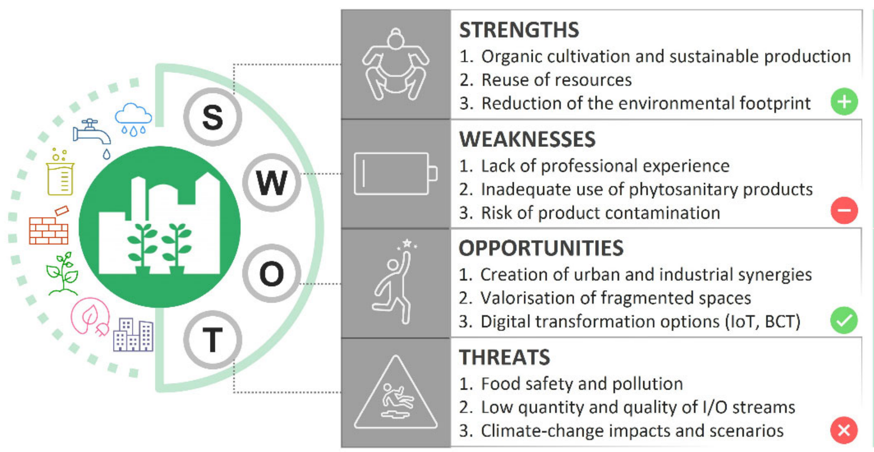

Figure 5. Strengths, weaknesses, opportunities and threats of nature-based agricultural solutions addressing the fifth urban circularity challenge to achieve circularity in cities.

The safety of food grown in the urban environment remains a concern in terms of soil, water, and air pollution [96]. Although research on the effects of pollution on UA is still scarce, there are several studies that assessed the feasibility and safety of vegetables grown in different urban spaces using UA-NBS, such as intensive green roofs (18) and urban farms and orchards (51), concluding that, in general, the concentrations of contaminants and trace metals found in the plants were below the European regulatory thresholds [97]. The following factors should be considered in order to determine the exposure of UA to pollutants in cities: (i) growing location, e.g., indoor or outdoor UA, soil-based, or soilless technologies; (ii) type of crop, e.g., leafy vegetables with a large leaf surface area are more exposed to atmospheric particles, and root vegetables are more exposed to soil contamination compared to fruiting vegetables; and (iii) soil and contaminant characteristics, e.g., ground-borne (root system) and air-borne pollution (plant above ground level) [97].

Climate change is a threat as well as an opportunity to the circularity of UA-NBS. As climatic conditions may determine the availability of resources, e.g., extreme precipitation events pose a challenge for rainwater harvesting, while even distribution of rainfall facilitates more efficient irrigation of green and productive areas, reducing dependence on external sources. Moreover, vegetated areas enhance evapotranspiration processes, which mitigates the duration of high air temperatures in cities [98]. Consideration of alternative sources may be necessary to ensure a successful operation and maintenance. Furthermore, city fragmentation and urban sprawl increase the heterogeneity of urban spaces that can be used for UA at different scales, enhancing the value of fragmented spaces (e.g., rooftops) and expanding the management options of urban areas [42]. The co-design of the UA-NBS in multidisciplinary teams would minimize uncertainty and provide insight into the city's potential.

Some circularity challenges were also recognized by Williams et al. [99] when identifying challenges to implementing looping actions, including technical constraints, linear resource systems, or the lack of circular planning and design in cities. Finally, in addition to the environmental benefits that UA-NBS provide, it is worth noting that they can also relieve societal challenges, such as food security, improved human health and well-being, sustainable urban development, or disaster-risk management [100,101].

4. Conclusions

Urban agriculture plays a key role in terms of a Circular City, as it can use recovered resources to produce new food and biomass. Thus, food and biomass production can contribute significantly towards closing the urban cycle, maximizing the reuse of resources in the urban environment while reducing the need for external resource inputs.

Greater commitment with urban agriculture would help to address urban circularity challenges. In this regard, nature-based solutions for food and biomass production contribute to address at least one urban circularity challenge. Certain nature-based solutions for food and biomass production can be circular in themselves, while others need nearby nature-based solutions or are strategically located to address other urban circularity challenges. In future, this descriptive approach can be underpinned by mathematical models, which would make it possible to support the theoretical approach with statistical data.

We analyzed how input and output resource streams related to food and biomass production are located as part of other resource streams to close the cycles within the urban metabolism, i.e., into and out of a Circular City. Design solutions geared towards closing loops, such as aquaponic farming, are targeted by urban agriculture in circular cities. A broader understanding of the food-related urban streams is important to recover resources and adapt the distribution system accordingly. For it, essential knowledge of the input and output streams is required in order to design, adapt, or couple urban agriculture-related nature-based solutions units and interventions and supporting units.

Additionally, the need for better knowledge, transversal research networks, governance, regulations, and policy strategies and dialogues to improve nature-based agricultural solutions in circular cities should be highlighted.

Supplementary Materials: The following are available online at www.mdpi.com/2073-4441/13/18/2565/s1, Figure S1: Potential of selected representatives urban agriculture-related NBS units and interventions (NBS_u/i) to address the fifth urban circularity challenge (UCC_5) on "Food and biomass production" [5–7], according to the score range (0.33, 0.66, 1.00) (cf. Tables 1 and 2). Numbers refer to those of NBS_u/i from Table 2. Color legend refers to the categories of NBS_u/i (cf. Table 2) [6,7]; Figure S2: Overview of input and output streams in urban agriculture with focus on water.

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Article

Towards a Cross-Sectoral View of Nature-Based Solutions for Enabling Circular Cities

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Abstract: A framework developed by the COST Action Circular City (an EU-funded network of 500+ scientists from 40+ countries; COST = Cooperation in Science and Technology) for addressing Urban Circularity Challenges (UCCs) with nature-based solutions (NBSs) was analyzed by various urban sectors which refer to different fields of activities for circular management of resources in cities (i.e., reducing use of resources and production of waste). The urban sectors comprise the built environment, urban water management, resource recovery, and urban farming. We present main findings from sector analyses, discuss different sector perspectives, and show ways to overcome these differences. The results reveal the potential of NBSs to address multiple sectors, as well as multiple UCCs. While water has been identified as a key element when using NBSs in the urban environment, most NBSs are interconnected and also present secondary benefits for other resources. Using representative examples, we discuss how a holistic and systemic approach could facilitate the circular use of resources in cities. Currently, there is often a disciplinary focus on one resource when applying NBSs. The full potential of NBSs to address multifunctionality is, thus, usually not fully accounted for. On the basis of our results, we conclude that experts from various disciplines can engage in a cross-sectoral exchange and identify the full potential of NBSs to recover resources in circular cities and provide secondary benefits to improve the livelihood for locals. This is an important first step toward the full multifunctionality potential enabling of NBSs.

Keywords: circularity challenges; multifunctionality; interdisciplinary; nature-based solutions; urban sectors; sustainable urban development; ecosystem-based management

1. Introduction

At present, there is a global concern regarding the effects of climate change and the long-term availability of natural resources such as water, especially in cities, where most of the world population is concentrated [1,2]. Cities consume more than 60% of the natural resources, produce 50% of all global waste, and produce more than 75% of all greenhouse gas emissions [3,4]. Therefore, the current paradigm of linear exploitation of natural capital, which is based on the principles of 'take–make–dispose' [5] is causing a significant environmental footprint. Thus, a paradigm shift moving toward the circular economy (CE), in which the use of resources is reduced through reuse and recycling approaches, is needed. Shifting toward circular management of resources requires systemic changes in human behavior and thinking, education, conceptual/technical/technological approaches, legislation, and governance. In this research, we explore nature-based solutions (NBSs) as facilitators toward circular change.

NBSs emerge as multifunctional and multiscale "green" technologies and solutions for reshaping the existing linear resource management into a circular one [6]. Currently, the design and use of NBS mostly focus on one specific urban challenge, e.g., to treat wastewater or to mitigate the urban heat island effect. However, NBSs have the potential to address several urban challenges simultaneously, specifically in relation to various Urban Circularity Challenges (UCCs). The following seven UCCs for shifting to a circular management of resources with NBSs were identified by Atanasova et al. [6]: UCC_1 "restoring and maintaining the water cycle", mainly by rainwater management; UCC_2 "water and waste treatment, recovery, and reuse"; UCC_3 "nutrient recovery and reuse" with a focus on nitrogen, phosphorus, and potassium; UCC_4 "material recovery and reuse", mainly as materials in the built environment; UCC_5 "food and biomass production" in sustainable ways in cities; UCC_6 "energy efficiency and recovery", including mitigation of the urban heat island effect, as well as heat and energy recovery from different waste streams; UCC_7 "building system recovery" related to the topic of regeneration of the built environment.

The COST Action CA17133 Circular City [7] aims to facilitate the use of NBSs to foster CE in urban environments. It defines NBSs as " ... *concepts that bring nature into cities and those that are derived from nature*". This definition includes processes for resource recovery that use organisms (such as microbes, algae, plants, insects, and worms) as the principal agents [7].

As a first step of the Action's work, the state of the art of NBSs to foster CE was reviewed, while bottlenecks and research questions were also identified. These reviews were prepared by the five Working Groups of the Action, i.e., built environment (WG1 [8]), urban water (WG2 [9]), resource recovery (WG3 [10]), urban farming (WG4 [11]), and transformation tools (WG5 [12]).

Furthermore, a framework for addressing UCCs with NBSs was defined [13]. The framework is aimed at mainstreaming the use of NBS for the enhancement of resource management in urban settlements. It comprises a set of 39 NBS units (NBS_u), 12 NBS interventions (NBS_i), and 10 supporting units (S_u), as well as the analysis of input and output (I/O) resource streams required for NBS units and interventions (NBS_u/i). The framework has been discussed from different perspectives that correspond to urban sectors and activities relevant for the potential of circular management of resources for the (1) built environment [14], (2) urban water management [15], (3) resource recovery [16], and (4) urban farming [17].

This paper demonstrates that a holistic, cross-sectoral approach of implementing NBSs is necessary to account for the full potential of NBSs by presenting urban sector perspectives and identifying the interconnection of different sectoral views in various fields of application. On the basis of our findings, we conclude that the full potential of NBSs relies on multifunctional solutions which address CE and foster the path toward creating and pursuing integrated management of circular cities.

2. Materials and Methods

The overall methodology included (i) a selection of most relevant UCCs for the unban sectors and related NBS_u/i that can address those UCCs, i.e., relevant for the sectors, (ii) the evaluation of the selected NBS_u/i in terms of UCCs, (iii) analysis of the participating disciplines in the research, (iv) a discussion, defining relevant input and output (I/O) streams, and (v) the evaluation of existing gaps, opportunities, and tradeoffs. The results of these analyses were summarized by identifying the main challenges addressed by the selected NBS_u/i, within the sectoral view.

2.1. Nature-Based Solution Concept under the Perspective of Different Urban Sectors

Within the COST Action Circular City, the NBS units and interventions (NBS_u/i) were analyzed under the perspectives of four selected urban sectors, which refer to the different fields of activities for circular management of resources in cities, namely, the built environment [14], urban water management [15], resource recovery [16], and urban farming [17]. With circularity always in focus, each sector first identified the most relevant UCCs being dealt with and then the most applicable NBS_u/i to address the relevant UCCs.

2.2. Evaluation of Nature-Based Solution Relevance to Urban Sectors and Related to the Urban Circularity Challenges

The list of NBS_u/i and S_u presented in Langergraber et al. [13] and Castellar et al. [18] was used as a basis for evaluating their relevance for the following urban sectors: building systems, building sites, urban water management, resource recovery, and urban farming. In this paper, urban sectors also correspond to the working groups of the COST Action Circular City, whereby the evaluation for the overall sector of built environment was separately done for building systems (the building itself) and building sites (including the surroundings of buildings).

The evaluation was carried out during a series of elicitation workshops under the scope of the COST Action Circular City, involving 71 experts on average from 28 countries. The participants identified, for each urban sector, a series of criteria (explained in Section 3.2.2) to select the most relevant NBS_u/i. Despite very specific criteria identified, a similar methodology was used across the different urban sectors, for the data to be comparable.

The extent to which NBS_u/i can address multiple urban sectors was based on the methodology presented by Langergraber et al. [13] to evaluate the potential of NBSs to address UCCs. In this sense, the selected NBSs for each urban sector were evaluated according to the following scores: (1) the NBS_u/i are relevant (score = 1); (2) the NBS_u/i might be relevant, depending on the system design (score = 0.5); (3) the NBS_u/i is not relevant (score = 0). To analyze the overall relevance of NBS for urban sectors, we calculated the following global scores: the "sector global score", by simply averaging the NBS scores for each urban sector, and the "NBS global score", by simply averaging the sector scores for each NBS_u/i. Indeed, the NBS global score represents the potential of each NBS to be used by different sectors, thus providing a cross-sectoral performance. We also counted the number of NBSs relevant for each urban sector and the number of urban sectors related to each NBS_u/i.

Additionally, the different selection criteria of each urban sector were discussed and analyzed to identify whether an NBS_u/i is relevant or not on the basis of their fields of application, to determine why perspectives differ among the experts, and to determine the NBS potential to address multiple sectors along with the UCCs.

2.3. Background Analysis of Workshop Participants and Their Experiences with Nature-Based Solutions

A short questionnaire was developed and sent to the participants of the 10 workshops held between March 2020 and April 2021, during which the new framework [13] of the COST Action Circular City was discussed and developed, to analyze the disciplines that contributed (one workshop was held in person, and the remaining nine workshops were held in a virtual setting). Each virtual Circular City workshop had an average of 71 participants—with a minimal participation of 59 members (second and third virtual workshops) and a maximal participation of 87 members (fifth virtual workshop)—from 28 countries. A total of 191 people participated in the workshops and received the questionnaire.

In addition to information on the nationality and residence country, the following questions were asked:

- What is your professional background? (Multiple answers possible)
- What is your professional activity?
- How would you rate your experience with NBS? (From 1: very low to 5: very high)
- How much did your participation in the COST Action Circular City help you to improve your expertise on NBSs?
- Please provide 1–3 keywords that summarize the potential of NBSs to address circularity in cities.

In total, 121 of the 191 persons (>60%) filled out the questionnaire. From the 57 persons that participated in at least five workshops, more than 90% responded; thus, the results can be considered as relevant for the persons mainly involved in the discussions from the Circular City workshops.

2.4. System Analyses of Resource Streams

Both environmental dimensions and urban sector conditions show how the NBS_u/i can differently address circularity, and the perception of how these NBS_u/i contribute to address UCCs can largely vary. Therefore, novel tools are required to successfully implement CE principles.

Some linear examples show the status quo regarding the urban water cycle: (1) water is a resource needed for irrigation of urban green and agriculture, as well as mitigation of the urban heat island effect, (2) runoff water needs to be managed using NBS to avoid pluvial flooding and relief pressure on the existing sewage system, and (3) wastewater is collected and transported to a treatment wetland where it is treated and discharged.

To support the transition toward circular resource flows, information on these streams is needed. System analysis was used to study the CE network topology (Figure 1). The network consists of nodes and links. Nodes are CE entities, circular city entities, or NBS units (NBS_u)—black boxes for which only input and output (I/O) are known. They are linked by resource streams. Since the nodes are seen as black boxes, system internal streams (which can also be circular) are not considered in the information model. Whether a stream is internal or external depends on the design of the model; ownership is usually a good delineation. For example, in a trans-aquaponics case, where a treatment wetland is used for aquaculture wastewater and sludge removal [19], internal streams become external if the coupled production units have different owners.

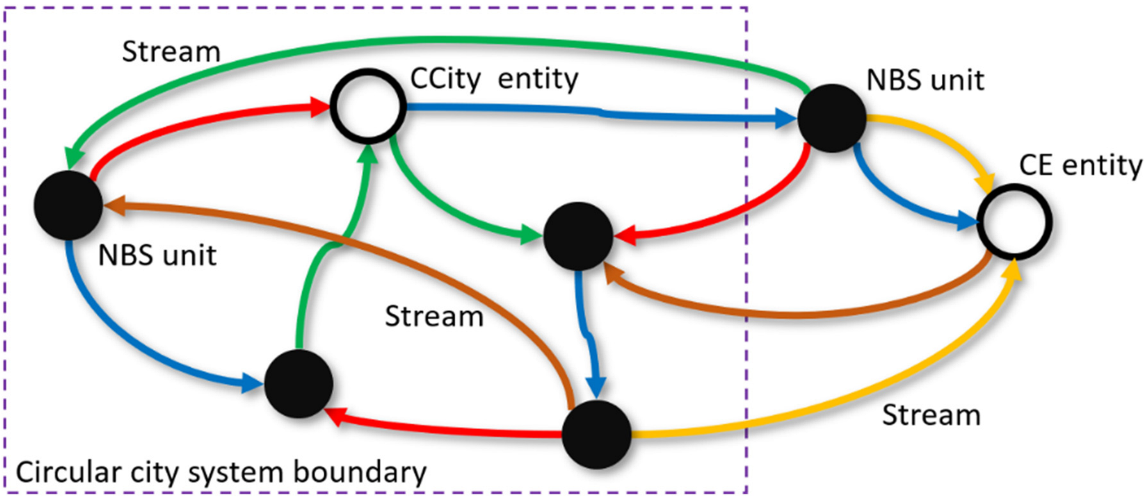

Figure 1. Schematic sketch of a CE network topology with CE and Circular City entities (referred to as "CCity entities") as black boxes (nodes) and unidirectional resource streams (links). Circular Economy entities (referred to as "CE entities") within the Circular City system boundary become Circular City entities. All full circles represent NBS units, regardless of the Circular City system boundary. The link colors symbolize the stream types of water, nutrients, biomass, living organisms, and energy but do not represent specific streams in this sketch.

A recently published model [20] was further developed by reducing its scope and concomitantly qualifying the model elements, adjusted to the requirements of the COST Action Circular City with a focus on streams as a 'streams information model'. It waived the site model element, integrated the 'extended resource specification' as stream properties, and added the circular city system boundary, allowing the circularity between NBS_u/i and other CE entities. A unified terminology was developed to describe the requirements for resource streams from and to NBS, which were applied to all streams, notwithstanding differences of the individual streams. In this model, we abbreviate NBS_u/i as NBS.

3. Results and Discussion

3.1. Nature-Based Solutions Units and Interventions and Supporting Units under the Perspective of Different Urban Sectors

The relevance of NBSs was analyzed from the perspective of different urban sectors. The main outcomes are summarized below.

- *Built environment*: Pearlmutter et al. [14] focused on building systems and identified the "wicked problem of water"; more provision of services by NBSs requires a higher water use, which is commonly solved by importing water from outside the city. The authors proposed to challenge this conundrum by focusing on those NBS_u/i classified as vertical greening systems and green roofs [13], and how they can be used to foster graywater reuse and capture available rainwater. This approach is based on the first and second urban circularity challenges (UCC_1 and UCC_2) [6] and is based on three steps: (i) how can NBS be integrated into buildings help to close the water cycle, (ii) how can water be incorporated into the life-cycle analysis (LCA) of a building as a resource, and (iii) how can the proposed solutions of graywater and rainwater reuse across different climates be modeled to allow comparisons. According to the LCA approach, the required water input was identified to have a significant impact on the water needs of NBSs and support the shift toward water reuse practices. However, as cities are often heterogeneous with diverse urban dwelling types, water reuse management needs to be planned and implemented at the neighborhood scale. This can be done successfully if existing gaps in policy are filled, and planning processes include inter- and multidisciplinary approaches from the initial stages. Building system recovery, one of the UCCs defined (UCC_7), was not directly addressed by Pearlmutter et al. [14]. Although CE itself does not distinguish among the scales of circularity, building reuse has often been agreed upon as a preferred option over material and component recycling, thanks to its higher upscaling potential. This is particularly true for "heritage" buildings and neighborhoods. In urban regeneration projects, NBSs can effectively be used to address this issue. Circular buildings positively impact materials, energy, waste, biodiversity, health and wellbeing, human culture, and society at once [21]. Additionally, they may produce multiple forms of value [22].

- *Urban water management*: Oral et al. [15] discussed the urban water management perspective with a special focus on UCC_1 and UCC_2. The 51 NBS_u/i and 10 S_u [13] were assessed in relation to their contribution to UCC_1 and UCC_2, by applying identification, categorization, and a semiquantitative ranking system for selecting the most relevant NBSs. Critical water streams for NBS_u/i and their use in addressing UCC_1 and UCC_2 were identified and complemented with case studies and evaluation tools. In this regard, challenges and barriers, as well as the opportunities and potential of NBSs to address urban water circularity, were identified and expanded.
- *Resource recovery*: Resource recovery from solid and liquid urban waste streams with the application of NBS units (NBS_u) was discussed by van Hullebusch et al. [16]. In the same study, supporting units (S_u) for producing recycled fertilizers, as well as disinfecting recovered products and separate streams, were presented. The efficiency of resource recovery was assessed for the systems where NBS_u/i and S_u were already tested and operated at micro- or mesoscale, and which are applicable in the urban environment (i.e., they have a Technology Readiness Level higher than 5). It has been pointed out that circular systems for resource recovery entail collection and transport infrastructure, treatment and recovery technology, and urban agricultural or green reuse. To enhance the efficiency of these systems for resource recovery, existing circularity, and application challenges dealing with infrastructure, legislation, social and environmental services, and multiple stakeholders must be tackled.
- *Urban farming*: Canet-Martí et al. [17] highlighted that urban agriculture plays a key role in circular cities. Urban agriculture can use recovered resources to produce food and biomass and, thus, contribute significantly toward closing the urban cycle, maximizing the (re)use of resources while reducing the need for external resource inputs. The expanded deployment of urban agriculture would help to address UCCs in general and UCC_5 in particular. This requires a better understanding of the food-related urban streams in order to recover resources and adapt to the distribution system accordingly.

3.2. Nature-Based Solution Relevance to Urban Sectors Related to Urban Circularity Challenges

3.2.1. Criteria to Define the Relevance of NBS Units and Interventions for Urban Sectors

For selecting relevant NBS_u/i for the four selected urban sectors, each sector identified the most relevant UCCs (Figure 2). During the evaluation process, all sectors had the generic UCCs in mind, i.e., maximizing efficiency in the use of water, energy, and materials, and minimizing waste products that cannot be cycled into further productive activities.

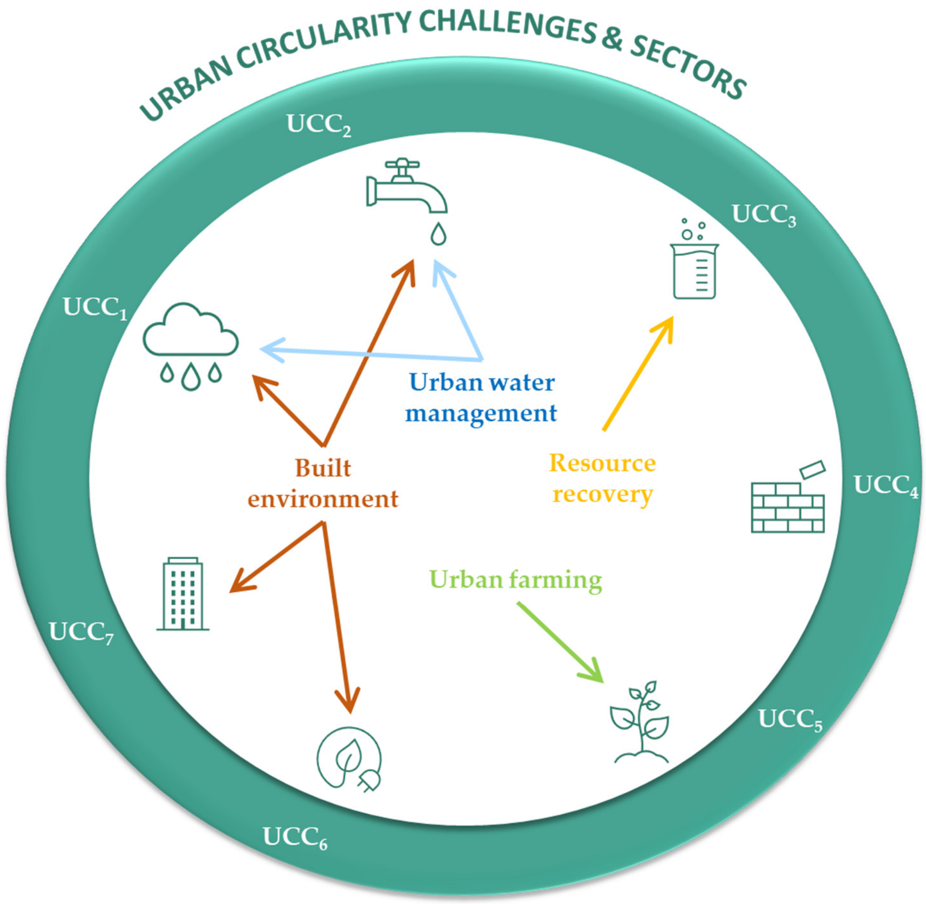

Figure 2. Most relevant Urban Circularity Challenges (UCCs) defined by the urban sectors for selecting relevant nature-based solution units and interventions (NBS_u/i). The arrows highlight the focus of the discussions in the urban sectors. Urban Circularity Challenges: UCC_1 = restoring and maintaining the water cycle; UCC_2 = water and waste treatment, recovery, and reuse; UCC_3 = nutrient recovery and reuse; UCC_4 = material recovery and reuse; UCC_5 = food and biomass production; UCC_6 = energy efficiency and recovery; UCC_7 = building system recovery.

Other specific criteria for selecting relevant NBS_u/i are described below.

- *Built environment*: In general, the relevance of NBS_u/i and S_u for the built environment was decided on the basis of their potential to address UCC_1, UCC_2, UCC_6, and UCC_7 (Figure 2). Furthermore, the different relevance of NBS_u/i for green building systems and sites [8] was considered. For the category of building systems, only NBSs directly connected to individual buildings are relevant. This mainly includes vertical greening systems and green roofs, as well as bioretention cells and S_u for rainwater harvesting. UCC_4 "material recovery and reuse" is part of the built environment as green building materials [8], although green building materials were not considered here except as components of vertical greening systems and green roofs. Food and biomass production is represented by NBS_u/i, which can be integrated as urban blue infrastructure, as green infrastructure in/on buildings, as green infrastructure as parks and landscapes, and/or as green infrastructure as urban farms, such as hydroponic and soilless technologies, and aquaponic farming (blue infrastructure, green infrastructure in/on buildings, and/or as urban farm), as well as productive gardens (as green infrastructure as parks and landscape and/or urban farms) [17]. For building sites, NBS_u/i are relevant when implemented within the urban landscape. This implementation requires the interaction of multiple disciplines, from landscape architecture to urban climatology, to successfully realize the potential of these nature-based strategies and integrate them into the city fabric [21].

- *Urban water management*: As water is intrinsic for the design and operation of most NBSs, almost all NBS_u/i from the urban water management point of view were selected as relevant (or "might be relevant", as defined in Section 2.2.), except for composting and a few S_u. The relevance of NBS_u/i and S_u was determined on the basis of their ability to address UCC_1 and UCC_2, by enabling processes such as conveyance, infiltration, retention, and treatment (including sedimentation, biodegradation, and sorption) [15]. In total, only 13 NBS_u/i were marked as "might be relevant", mainly NBS_i for soil and water bioengineering, as well as NBS_u for food and biomass production.
- *Resource recovery*: Relevant NBS_u/i and S_u can generate new or recover resources from urban solid and liquid resource flows, whereby the focus was on UCC_3 "nutrient recovery and reuse" to gain appropriate quantity and quality of resources. Not surprisingly, van Hullebusch et al. [16] identified most of the NBS_u/i and S_u that are targeted to remediation, treatment, and recovery as relevant. However, they did not focus on other resources such as materials (UCC_4) and energy (UCC_6), water (UCC_1 and UCC_2, as already covered by urban water management), and biomass (UCC_5, covered by urban farming).
- *Urban farming*: NBS_u/i and S_u were assessed for potentially contributing to UCC_5, evaluating food and biomass production separately. The NBS_u/i and S_u considered relevant for urban farming were (i) those with food and/or biomass production as their main purpose (addressing and contribution to the UCC_5), i.e., those that produce a relevant amount of food and/or biomass (outputs) or consume it for their operation (inputs), e.g., "composting" and "biochar", as well as (ii) those that can produce food and/or biomass (potential contribution to UCC_5) when designed for that purpose (system design), such as those classified as vertical greening systems and green roofs, and (public) green space [17]. The 10 NBS_u/i considered as "might be relevant" are intrinsically composed of vegetation although they are not designed for food and/or biomass production. Most of them are used for rainwater management. NBS_i such as "coastal soil erosion", "erosion control", and "riverbank engineering" were included as "might be relevant" as the actions and infrastructures can be designed to function as areas for food and/or biomass production [17].

3.2.2. Evaluation of the Relevance of Nature-Based Solutions for Urban Sectors

Table 1 presents the relevance of the NBS_u/i and S_u for the different sectors, according to the selection criteria discussed in the previous chapter. The NBS global scores and number of relevant sectors for each NBS_u/i are shown in Figure 3.

Table 1. Relevance of NBS units and interventions (NBS_u/i) and supporting units (S_u) for different sectors, i.e., working groups of the COST Action Circular City (• = relevant; ○ = might be relevant, depending on system design). NBS_tu = technological units; NBS_su = spatial units; NBS_is = soil interventions; NBS_ir = river interventions; S_u = supporting unit.

Classification		(#) NBS Units and Interventions, and Supporting Units	Urban Sectors *Building Systems*	*Building Sites*	*Urban Water Management*	*Resource Recovery*	*Urban Farming*
Rainwater Management	*NBS_tu*	(1) **Infiltration basin**		•	•	•	○
		(2) **Infiltration trench**		•	•	•	
		(3) **Filter strips**		•	•		
		(4) **Filter drain**		•	•		
		(5) **(Wet) retention pond**		•	•	•	○
		(6) **(Dry) detention pond**		•	•		
		(7) **Bioretention cell**	•	•	•		○
		(8) **Bioswale**		•	•		○
		(9) **Dry swale**		•	•		○
		(10) **Tree pits**		•	•		○
		(11) **Vegetated grid pavement**		•	•		○
		(12) **Riparian buffer**		•	•		•
	S_u	(S1) **Rainwater harvesting**	•		•		
		(S2) **Detention vaults and tanks**	•		•		

Table 1. *Cont.*

Classification		(#) NBS Units and Interventions, and Supporting Units	Urban Sectors *Building Systems*	*Building Sites*	*Urban Water Management*	*Resource Recovery*	*Urban Farming*
Vertical Greening Systems and Green Roofs	*NBS_tu*	(13) **Ground-based green facade**	•		•		•
		(14) **Wall-based green facade**	•		•		•
		(15) **Pot-based green facade**	•		•		•
		(16) **Vegetated pergola**	•	•	○		•
		(17) **Extensive green roof**	•		•		•
		(18) **Intensive green roof**	•		•		•
		(19) **Semi-intensive green roof**	•		•		•
		(20) **Mobile green and vertical mobile garden**		•	○		•
Remediation, Treatment and Recovery	*NBS_tu*	(21) **Treatment wetland**	•	•	•	•	•
		(22) **Waste stabilization pond**			•		
		(26) **Anaerobic treatment**			•	•	
		(27) **Aerobic (post) treatment**			•	•	
	NBS_is	(23) **Composting**	•	•		•	•
		(24) **Bioremediation**		•	○	•	
		(25) **Phytoremediation**		•	○	•	•
	S_u	(S3) **Phosphate precipitation** (for P recovery)			•	•	
		(S4) **Ammonia stripping** (for N recovery)			•	•	
		(S5) **Disinfection** (for water recovery)	•		•	•	
		(S6) **Biochar/hydrochar production**			•	•	•
		(S7) **Physical unit operations for solid/liquid separation**			•	•	•
		(S8) **Membrane filtration**			•	•	
		(S9) **Adsorption**			•	•	
		(S10) **Advanced oxidation processes**			•	•	
(River) Restoration	*NBS_ir*	(28) **River restoration**		•	•		•
		(29) **Floodplain**		•	•		•
		(30) **Diverting and deflecting elements**		•	○		
		(31) **Reconnection of oxbow lake**		•	•		
		(32) **Coastal erosion control**		•	•		○
Soil and Water Bioengineering	*NBS_is*	(33) **Soil improvement and conservation**		•	○	•	•
		(34) **Erosion control**		•	○		○
		(35) **Soil reinforcement to improve root cohesion and anchorage**		•	○		
		(36) **Riverbank engineering**		•	○		○
(Public) Green Space	*NBS_su*	(37) **Green corridors**		•	•		•
		(38) **Green belt**		•	•		•
		(39) **Street trees**		•	•	•	•
		(40) **Large urban park**		•	•	•	•
		(41) **Pocket/garden park**		•	•	•	•
		(42) **Urban meadows**		•	•		•
		(43) **Green transition zones**		•	•		•
Food and Biomass Production	*NBS_tu*	(44) **Aquaculture**					•
		(45) **Hydroponic and soilless technologies**	•		○		•
		(46) **Organoponic/bioponic**	•		○		•
		(47) **Aquaponic farming**	•		○		•
		(48) **Photo bioreactor**			○	•	•
	NBS_su	(49) **Productive garden**	•	•	•		•
		(50) **Urban forest**		•	•		•
		(51) **Urban farms and orchards**		•	•		•

Only five NBS_u/i were selected as relevant by all sectors (whereby building systems and building sites are considered as one sector, i.e., built environment), namely, treatment wetlands, phytoremediation, street trees, large urban parks, and pocket gardens/parks:

1. Treatment wetland (#21) is a treatment technology inspired by natural wetland processes, being a highly versatile system that can be adapted to spaces and designed on the basis of their specific application [23]. Treatment wetlands can retain rainwater, as well as treat wastewater and graywater at the building scale for reuse as irrigation water (relevant for built environment and urban water management) and have the potential to recover nutrients taken up by roots and generate new resources such as biomass for bioenergy or as building material (relevant for resource recovery and urban farming).
2. Phytoremediation (#25) is a bioremediation process involving plants and microorganisms that removes, stabilizes, and/or degrades contaminants in the soil, water, and/or

air. The process can be deployed in the built environment, with consequent protection of water resources (urban water management). This may generate resources such as biomass, metals, and treated/regenerated soils, water, and air and is, thus, relevant for resource recovery and urban farming.

3. Street trees (#39) are important NBS_su, which are already systematically included in urban planning (built environment). They have the capacity for water retention, shading, and evapotranspiration, contributing to cooling, restoring the water cycle, enabling water reuse (urban water management, resource recovery), and reducing noise and air pollution (built environment). Street trees generate biomass for different applications, as well as food—either for direct consumption or for the food industry (relevant for resource recovery and urban farming). Thanks to their shading and evapotranspiration, trees are also very effective in reducing the energy needs of buildings and the thermal stress of pedestrians (built environment).
4. Large urban parks (#40), with a surface area greater than 0.5 ha, offer many possibilities to address UCCs. They constitute important green infrastructure for sustainable urbanization (built environment). Their vegetation and the expanse of permeable soil make them an outstanding NBS_su for water infiltration and retention, facilitating water reuse. They reduce further mitigation of pollutants along urban cycles and food chains, regulate the microclimate, and mitigate extreme weather events (urban water management). Their evapotranspiration and shading have a cooling effect, as well as an effect of reducing noise and air pollution (built environment). Their size allows for significant biomass and food production (resource recovery and urban farming) or covering renewable energy needs (built environment). Large urban parks offer several ecosystem services, e.g., space for recreation and social gatherings and, as such, contribute to human health.
5. Pocket/garden parks (#41) contribute to the same processes and address the same UCCs as large urban parks, albeit at a different scale (<0.5 ha); therefore, they can also be considered relevant for all urban sectors.

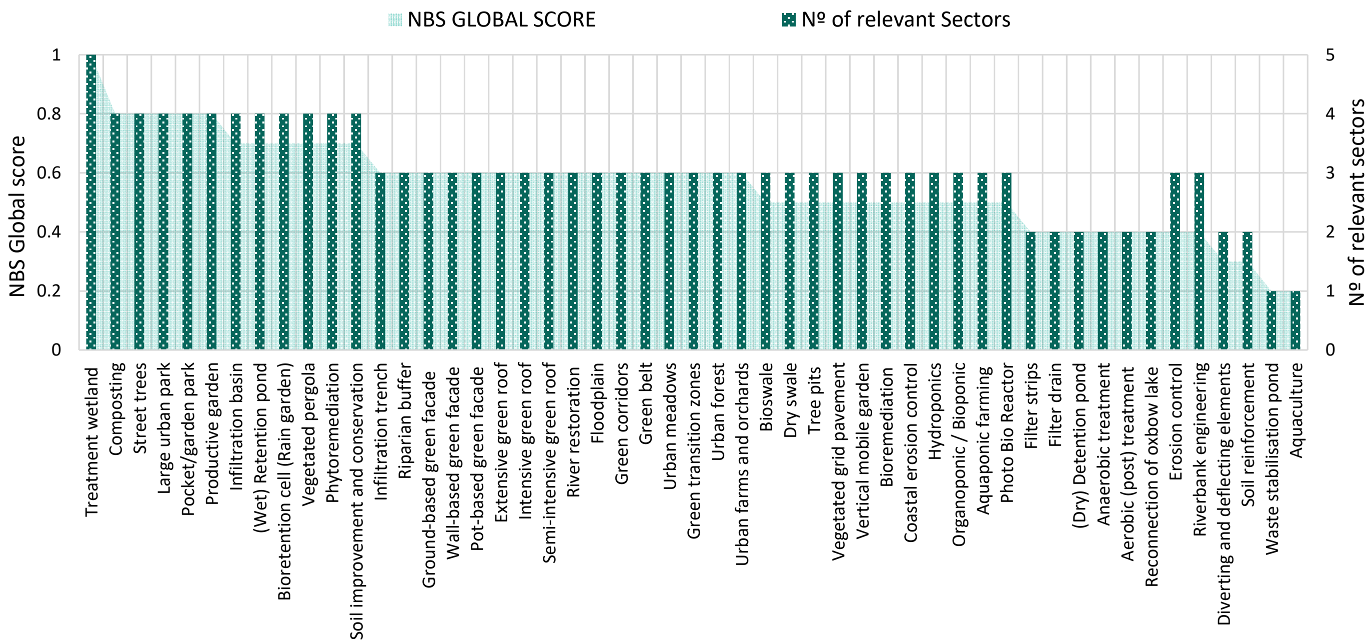

Figure 3. NBS global scores and number of relevant sectors for each unit and intervention (NBS_u/i). The NBS global score describes how many urban sectors selected a specific NBS_u/i as relevant (data from Table 1).

Not only are NBS_u/i selected by all urban sectors (Table 1) of interest, but those that have not been selected by specific sectors are also of interest, as well as the reason for their non-selection. As an example, the built environment did not select S_u for "remediation, treatment, and recovery" (#21–25 and S3–S10). This is of interest as those S_u can be identified as key technologies for onsite resource recovery and need to be integrated in the buildings to support circularity [16,24]. On the other hand, resource recovery did not select "vertical greening systems and green roofs" (#13–20). This can be explained by the applied criteria, specifically, the primary focus on nutrient recovery and usage within the city, including quantity and quality, and not on water circularity. Vertical greening systems and green roofs represent very effective NBSs for closing the water cycle at the building scale [24–27]. Both vertical greening systems and green roofs are suitable to be implemented in buildings across district and neighborhood scales, thus contributing to UCC_7 "building system recovery". NBS_u/i for "(river) restoration" and "soil and water bioengineering" were also not selected by resource recovery, thus indicating a low potential for nutrient recovery in the city.

Figure 4 summarizes the global sector scores and number of relevant NBS_u/i for each urban sector. The global sector scores are correlated with the number of relevant NBS_u/i. Urban water management was found to have the highest global sector score and most NBS_u/i were selected by this urban sector. On the contrary, building systems and resource recovery had the lowest global sector scores, and the fewest NBS_u/i were selected by these sectors. However, it should be considered that the list of NBS_u/i [13] does not include all possible NBS_u/i but only those with relevance to at least one UCC. Additionally, resource recovery discussions in the COST Action have focused, as mentioned above, on nutrient recovery, and other resources such as water, energy, and materials have not been the main focus or have been included in discussions of other sectors (e.g., water in urban water management).

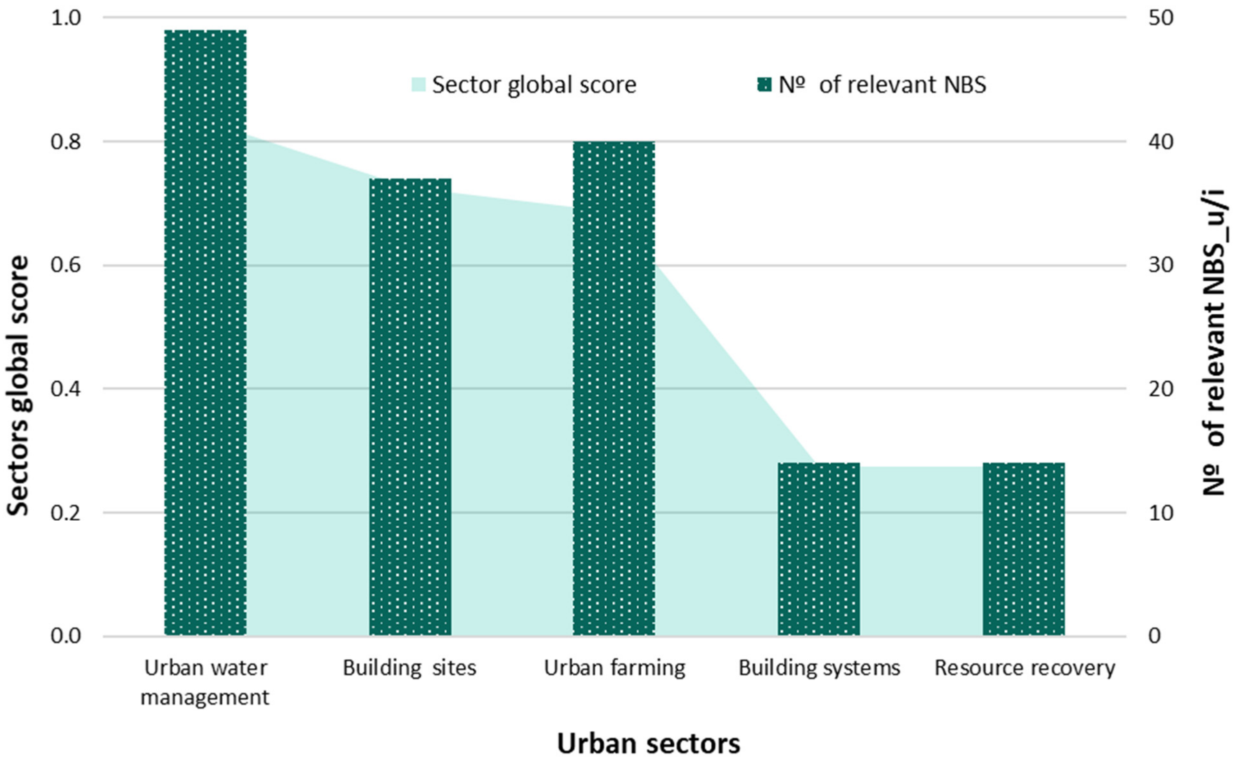

Figure 4. Global sector scores and number of relevant NBS units and interventions (NBS_u/i) for each sector. Global sector scores describe how many NBS_u/i were identified by each urban sector.

An important aspect related to systems design requires special attention; most of the NBS_u/i were selected as appropriate by more than one urban sector. However, to be multifunctional, i.e., address more UCCs simultaneously, a proper design and circular thinking are essential. For example, a vertical greening system may be designed for energy efficiency of a building only, where the design requires the use of tap water. Employing circular thinking would guide toward different designs, i.e., one that uses wastewater for irrigation and possibly utilizes plants used for biomass production. In this way, multiple challenges are addressed simultaneously by implementing different (resource oriented) designs, as explained in more detail in the next section.

3.2.3. Relationship between Sector Relevance and Ability to Address Urban Circularity Challenges

The potential of different NBS_u/i to address multiple UCCs and multiple sectors is shown in Figure 5. The potential to address multiple UCCs was presented by Langergraber et al. [13], and the values were derived from there.

Overall, there is a tendency that NBS_u/i with potential to address multiple UCCs also have the potential to address multiple sectors. NBS_u/i in quadrant I (potential for addressing multiple UCCs and sectors, both below 0.5) address only a limited number of UCCs and are relevant only for a few sectors. For instance, three out of four NBS_u/i from the category "soil and water bioengineering" can be found in quadrant I. In contrast, NBS_u/i in quadrant IV (potential for addressing multiple UCCs and sectors, both higher than 0.5) address various UCCs and are relevant for most sectors. For instance, seven out of eight NBS_u/i from the category "vertical greening systems and green roofs" can be found in quadrant IV. All NBS_u/i from the category "(river) restoration" are in quadrants I and II, indicating that the potential to address multiple UCCs is limited, whereas all NBS_u/i from the category "(public) green space" can be found in quadrants III and IV, indicating that they all have a very high potential to address multiple UCCs. The majority (seven out of eight) of the NBS_u/i from the category "food and biomass production" can be found in quadrants II and IV, indicating that they all have a high potential to address multiple sectors.

Defining the scale of environmental dimensions is essential to adequately define the system boundary of the impacts and the circularity of NBS. The environmental dimensions include spatial, temporal, thematic, and sectoral dimensions. The definition and the characterization of these dimensions are essential for the overall efficiency assessment of any NBS.

The spatial dimension can range from household to building to community scale, and to city, to regional, countrywide, continental, or even global scale. For instance, on a global scale, the water cycle is closed through evaporation/evapotranspiration and precipitation; however, on a local scale, reusing and recycling water can be of vital importance to reduce wastage and enhance sustainability. The temporal scale is just as important, as resources might regenerate in the long term, whereas, on a short timescale, they might be overused. The thematic dimension limits the system boundary to relevant topics. A restricted system boundary might exclude relevant cycling aspects and provide a biased impact of the holistic approach. The sectoral dimension accounts for the activities involved in the NBS. If a specific urban sector is excluded, it might reveal bias in the entire circularity of the NBS.

An illustrative example is represented by vertical greening systems, which contain different types of plants. The plants are mostly planted in a growth medium. Their spatial dimension is often limited to one building; accordingly, their system boundary is frequently limited to one wall. While some water can be recovered and purified by vertical greening systems, most precipitation water on a larger scale is lost, and the vertical greening systems do not appear to be an efficient water circulator. However, in the direct vicinity of the wall, vertical greening systems appear to have a significant effect on storing water in the soil and recovering evaporated water. A similar conclusion can also be drawn for the temporal dimension; in the short term, vertical greening systems can limit water runoff by storing or even recycling through evapotranspiration and condensation. However, on a longer timescale, water will eventually cross the local system boundary, revealing a low circularity efficiency. The thematic dimension is also crucial, since the benefits of vertical greening systems are not limited to local water recovery but extend to water purification, local cooling effects, enhancing biodiversity, improving air quality, and upgrading the comfort for residents. Lastly, depending on the sectoral perspective, the same effects can be considered with contradicting annotations. For instance, the increase in biodiversity might be perceived as a welcome benefit, while others might perceive the increase in insect population as a nuisance.

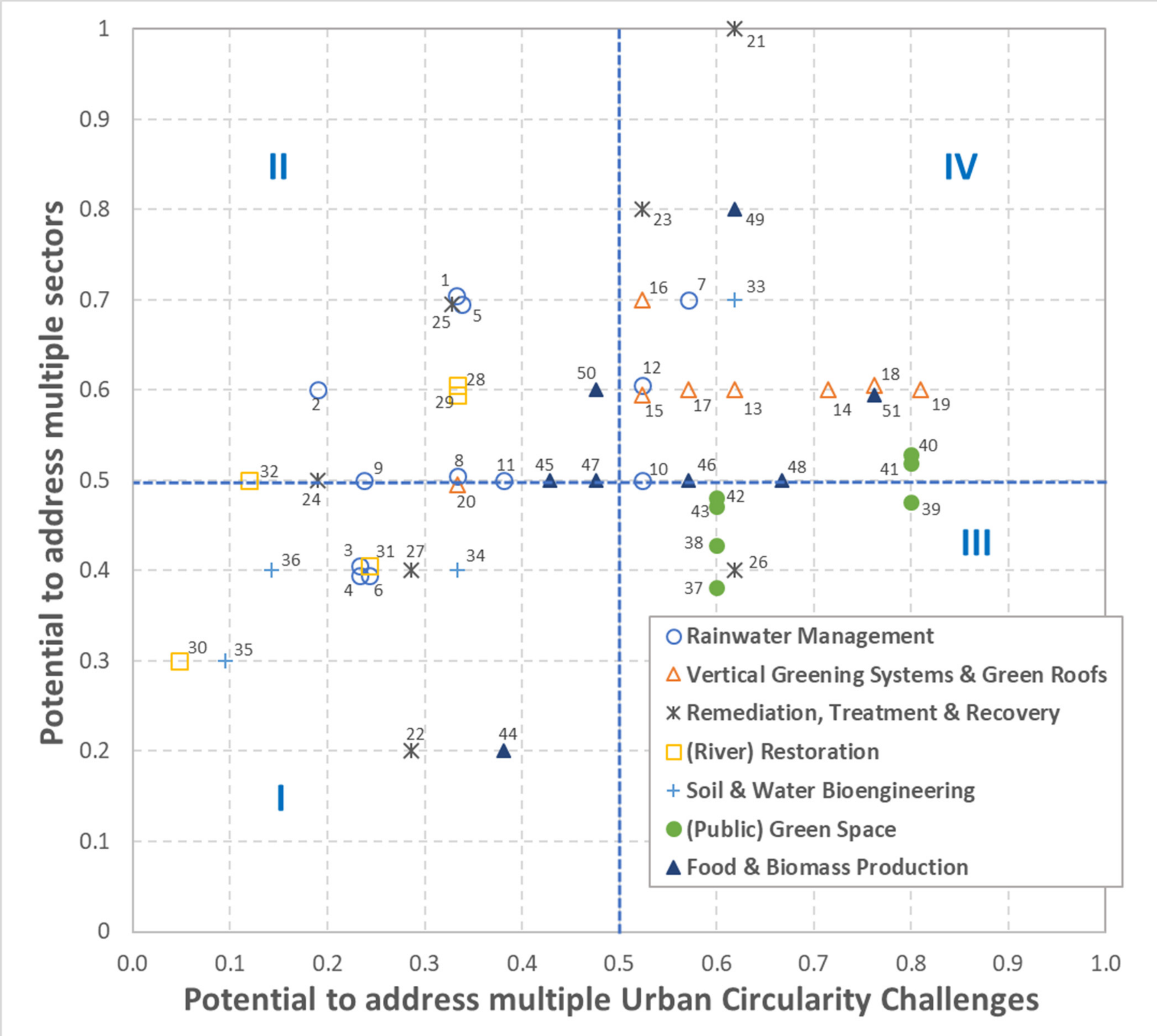

Figure 5. Potential of NBS units and interventions (NBS_u/i) to address multiple Urban Circularity Challenges (UCCs) and sectors. The numbers refer to numbers of the NBS_u/i in Table 1, and the different symbols refer to the categories of NBS_u/i [13]. NBS_u/i in quadrant I have lower potential to address multiple UCCs and sectors compared to NBS_u/i in quadrant IV.

Overall, the environmental dimensions of the system boundary of an NBS should be defined in careful consideration of spatial, temporal, and thematical aspects to assure a proper consideration of the full circularity. Lastly, a holistic system analytical approach is essential to provide a full assessment of the NBS. Accordingly, it is recommended to design NBSs while considering that they account for multiple challenges, including the complementarity of NBS_u/i, and they require the involvement of a wide variety of sectors and disciplines.

3.3. Participant Survey

The distribution of the professional background of participants was rather similar between all participants and those that participated in more than 50% of the workshops (Table 2). Although the participants had various professional backgrounds, engineers were dominant, and natural and social scientists were the minority. This reflects the composition of scientists participating in this COST Action.

When compiling the answers from all participants of the Circular City workshops, the keyword summarizing the potential of NBSs to address circularity in cities most often mentioned was "*water*" (Figure 6, hexagon in the left). However, when analyzing the keywords related to the professional background of the participants, the most often mentioned keywords were "*water management*" (agronomy, architecture), "*resources management*", "*resource reuse*", and "*recycling*" (agronomy, chemistry, urban and landscape planning), "*sustainability*" (engineering), "*climate change*" (chemistry, social sciences), and "*biodiversity*" (biology and geosciences). This highlights the different focus of the sectors on the use of NBSs and the importance of having a diverse and multidisciplinary research team to harness the full potential of NBS application in cities.

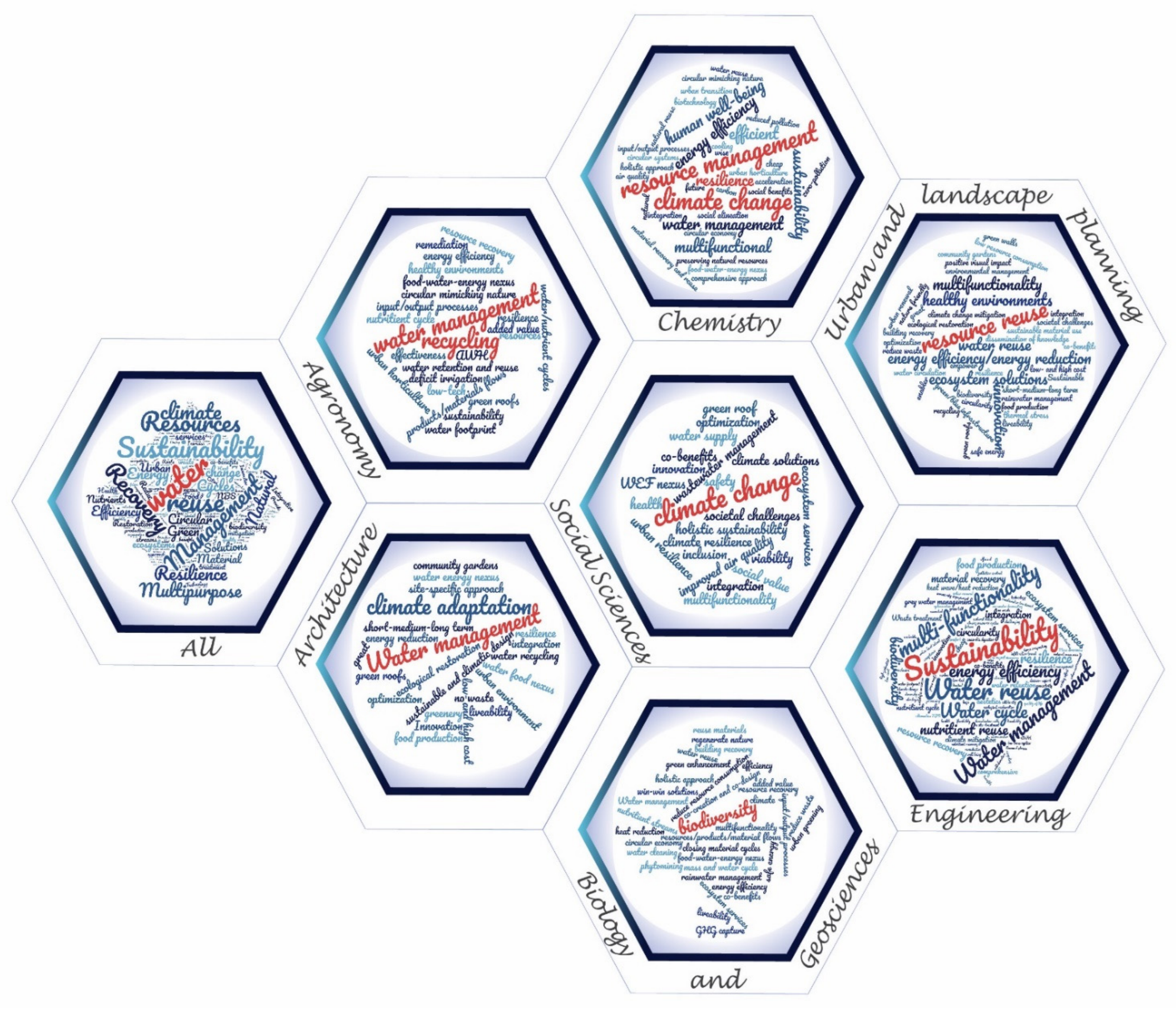

Figure 6. Word cloud of submitted keywords summarizing the potential of NBS to address circularity in cities, based on the reply from all participants (hexagon in the left) and participants with different professional backgrounds.

Table 2. Professional background of participants in the Circular City workshops.

Professional Background	Civil/Sanitary/ Env. Engineering	Agronomy/ Agricultural Engineering	Architecture	Urban/Landscape/ Rural Planning	Chemistry/ Biotechnology	Biology/ Geo Sciences/ Geology	Social Sciences
Participants >50% participation	52.5%	6.5%	5.6%	9.0%	11.6%	10.7%	4.0%
All participants	48.5%	5.3%	5.8%	10.4%	12.4%	8.6%	9.0%

3.4. A Streams Information Model to Describe Inputs and Outputs

A streams information model was developed to be able to represent the elements of a CE network topology in a unified way. This model is a specialization and further development of a predecessor [20].

The first part of the model (Figure 7) comprises CE entities as the nodes and refer to an entity type which is qualified by attributes, e.g., 'is natural feature'. In the present model, NBSs are considered special cases of CE entities, marked as 'is NBS unit', and comprise all NBS_u/i and S_u [13]. The concrete instance of an NBS_u/i or S_u has a name as a unique identifier and is located at a concrete place, and, if this location is within the system boundaries of the circular city, the property 'within circular city boundary' is set, making the NBS an entity of the circular city (CCity entity). In an implementation of the model, the assignment can be done automatically by a geographical information system (GIS).

The links between the CE entities are resource streams, which are hierarchically ordered by a complete set of types (water, nutrients, biomass, living organisms, and energy), divided into categories and subcategories, depicted by a comprehensive set of examples. Furthermore, they have a measuring unit which qualitatively describes a stream and can be used to quantify the flow volume. Streams have different endpoints: CE/CCity entities, NBS_u/i, or natural features, such as the atmosphere as a source of precipitation. Each NBS_u/i has at least one input (I) and one output (O) stream such that their cardinality is 1 to *n* in each case.

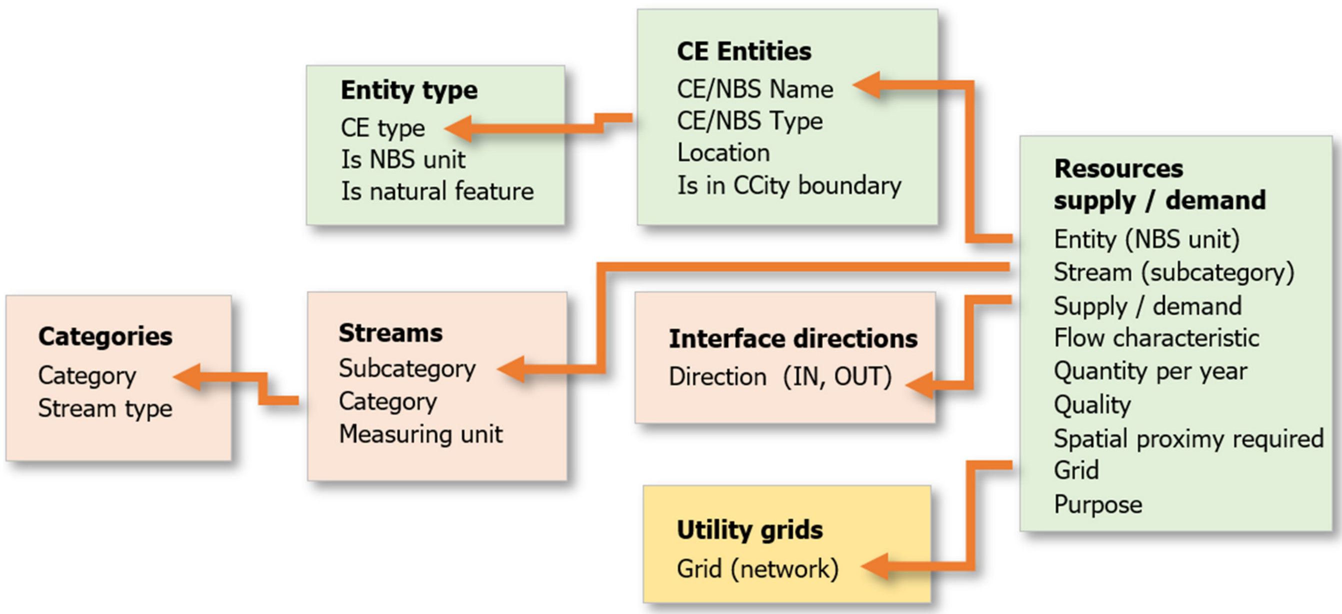

Figure 7. An information model on NBS_u/i and interconnecting streams (Figure 1). Green: entities and their resources; red: streams; yellow: grids (optional).

In conjunction with the endpoints, streams represent resources that are uniquely identified by (1) the entity (e.g., NBS_u/i or S_u) which is using a stream, (2) the stream subcategory, and (3) the interface direction of the NBS_u/i where 'input' is equal to demand

and ‘output’ is equal to the supply of the respective stream. Whether a stream is output (O) or input (I) depends on the respective endpoint. The resources have optional properties, such as flow characteristics, which describe whether a resource is permanently available, discontinuous, on demand, or adaptable. However, the annual quantity, statements on quality, whether spatial proximity is required, the possible use of utility grids, or the purpose of the resource can also be specified.

A stream connects two endpoints directionally and runs as output (O) from one endpoint to the input (I) of the other endpoint. This simplest form of resource use is linear and can occur in isolation in many places in the city. However, to implement a resource network which features circularity, it is necessary to connect these linear elements so that they form loops. Various loops can be formed within the system boundaries of the circular city; however, to create this network of loops, data on the quality and quantity of streams are required to fit the supply/demand of the respective endpoints. Nevertheless, there is still a considerable need for interdisciplinary research in order to be able to determine these stream characteristics.

The streams information model can be understood as a template, and there are many options to operationalize it. It can be reduced to a simple table, placing the information range into rows and columns. For example, the columns ‘type, category and the subcategory of stream’ in conjunction with ‘output from/input to NBS’ applied to the rows ‘biomass’ and ‘living organisms’ give a good overview on the material flows and their possible circularities within the sector of urban farming [17]. Resources are required or produced during operation and maintenance of NBS, input and output (I/O) streams need to be defined, and there is a gap between potential users and providers of resources [13]. To solve this problem, a relational database schema can be derived from the streams information model to implement a database, thus improving the resource management in cities.

3.5. The Current Sectoral View against a Much-Needed Holistic/Systemic Approach to Circular Management of Resources in Cities

While, conceptually, the solutions for closing material cycles are clear and favorable, practical implementation can be quite problematic, simply due to realistic mass balances of elements. Specifically, closing the nitrogen cycle, for example, by recovering it from urine may require a great deal of plant consideration to be effectively assimilated and later used for food. Plant seasonality is also one of the important aspects to be considered. All this requires innovative thinking and an adaptable design approach, and the proposed streams information model can be of great assistance. Another way to approach the coupling of processes is via the stoichiometry of the elemental composition. Both nutrient limitation and accumulation of undesired substances in a circular process reflect the matching of elemental composition of the material streams.

There are 92 naturally occurring elements on Earth. Only about 30 of the naturally occurring elements are widespread on Earth, and very few are important for life [28]. The frequency and the availability of elements in the Earth crust do not match their frequency in living beings. Furthermore, living beings contain different fractions of some elements. Plants, for example, require 17 essential nutrient elements [29] and generally contain lower fractions of nitrogen (contained mainly in proteins) and phosphorus than animals.

This can be illustrated using the case study of aquaponic systems, which approaches the emerging and inclusive CE paradigm [30], boosting its rich runoff effluents in terms of nutrient recycling (e.g., from nitrogenous fish waste) and fish wastewater treatment (i.e., in recirculating aquaculture systems) and, thus, minimizing external waste (nutrients and water) streams. Aquaponics is a sustainable food and/or biomass production NBS_u in which aquatic organisms (aquaculture) are coupled with horticultural soilless crop production (hydroponics), with the metabolic wastes produced by the fish being transformed via nitrification (bioremediation) for use as fertilizers (nutrients) for plants. These processes were recently investigated in depth [30–33]. A case study in Berlin (Germany) showed that the total demand for fish and vegetable production (tomato and lettuce) could be provided by aquaponics [34].

The aquaculture part of the aquaponic system provides most plant nutrients at lower concentrations as compared with the standard hydroponic solutions used for vegetable cultivation [35]. Moreover, the ratios between these elements are highly variable, ranging from 1.2 to 138.7 [36].

On one hand, this mismatch causes nutrient limitations of plant growth, which requires targeted nutrient supplementation to ensure healthy and abundant crop. On the other hand, non-assimilated nutrients accumulate in the recirculating water [37]. This problem must be tackled by adding technological steps to the aquaponic system, such as denitrification [38] or desalination [39], or by extending the system with specific crops that can utilize the available excessive elements [40]. This case study indicates the complexity of circular management of resources in cities.

4. Conclusions

The following conclusions can be drawn:

- Water is a key element when using NBS in the urban environment.
- The relevance of NBSs in different sectors is changing on the basis of their application in the Circular City. However, there is still a disciplinary bias toward the classical field of application, whereby different sectors implement the same NBS units and interventions with different designs and purposes.
- Multifunctionality is often discussed; however, it is rarely fully implemented. Thus, the potential of NBSs to address multifunctionality is usually not fully utilized.
- Cross-sectoral collaboration is essential in the design process for utilizing the full potential of NBSs in simultaneously addressing multiple urban challenges. New tools, such as the presented streams information model, can represent complete loops, i.e., resource flows through NBSs. Thus, they can facilitate circular thinking in the design process and integrate sectoral views for a better and multifunctional design of NBSs.
- The environmental dimensions of the NBS system boundary should be defined in careful consideration of spatial, temporal, and thematical aspects to assure circularity.
- Illustrative examples of vertical greening system and aquaponics show that the need for closing cycles is clear and favorable, but this requires innovative thinking and an adaptable design approach where input and output streams and users and providers of resources are well defined to facilitate practical implementation.
- Lastly, the COST Action Circular City served as an excellent platform for communicating and working across disciplines and sectors. Experts in engineering, architecture, planning, and natural and social sciences contributed to the work. Despite most participants belonging to the first group, this is a valuable attempt at crossing disciplinary gaps toward implementing the full potential of NBSs for the circular management of resources.

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