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COST Action CA17133

Implementing nature-based solutions for creating a resourceful circular city

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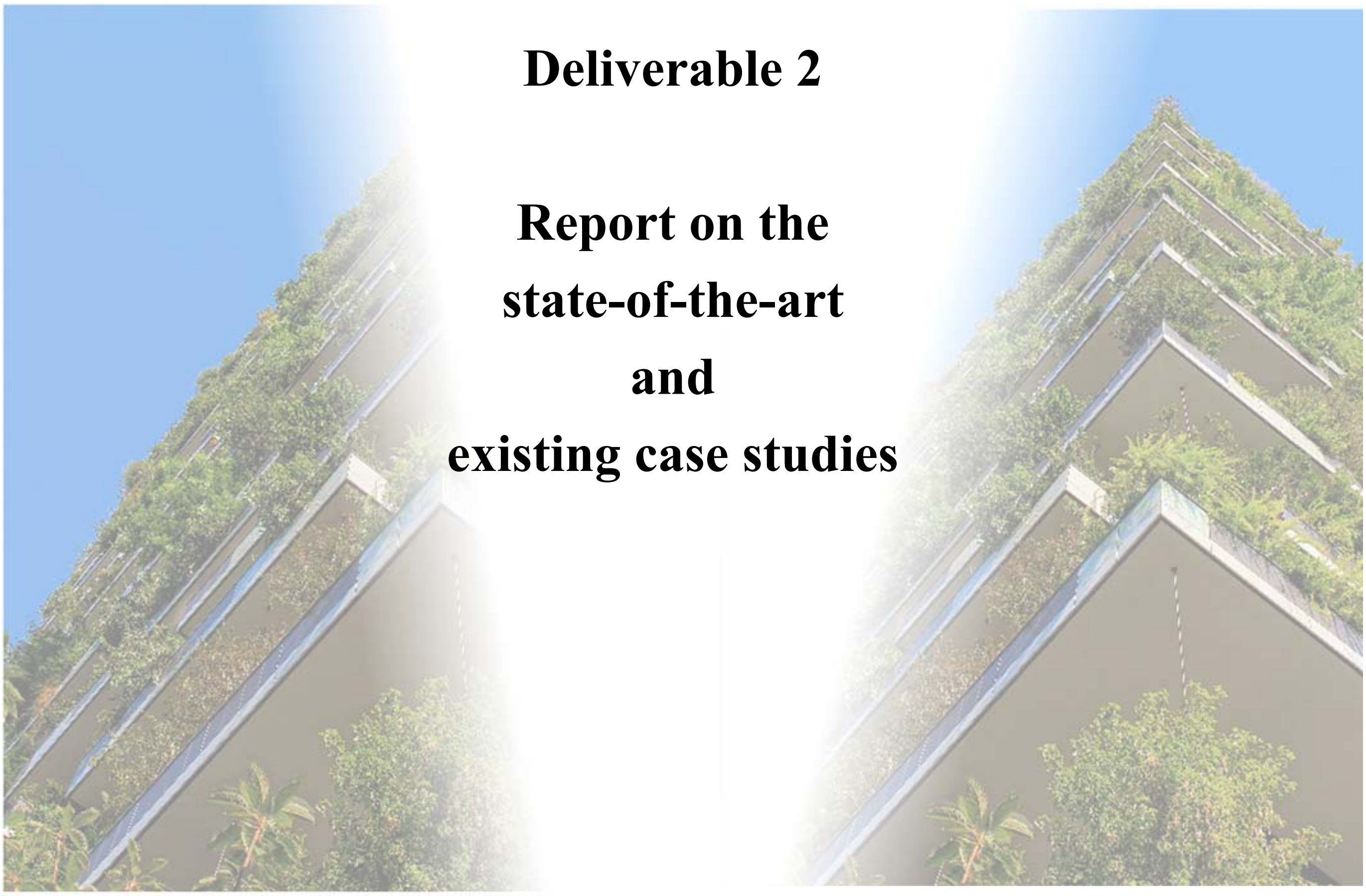

Deliverable 2

Report on the state-of-the-art and existing case studies

EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

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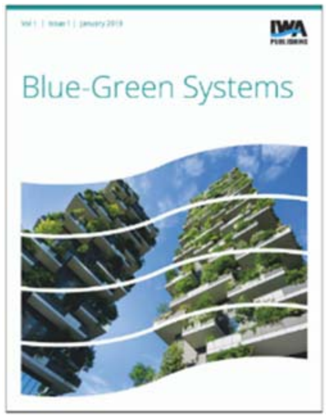

For this deliverable, the COST Action Circular City launched a Special Issue on "Towards Circular Cities" in the new IWAP Open Access on-line journal *Blue-Green Systems* (https://iwaponline.com/bgs).

In total six papers were prepared for this Special Issue, one introductory paper as well as five state-of-the-art review papers from the Action's five Working Groups. In total 105 persons from 35 COST countries contributed to the review papers.

The papers have been submitted end of June 2019, three of the papers are already accepted for publication while the other three papers have been submitted in revised versions and are expected to be accepted for publication soon. Publication of the Special Issue is expected in early 2020. The deliverable presents the papers of the Special Issue. The following table provides an overview on the review papers, contributors and status (as per 1 Nov 2019).

#	First author	Title	# authors	# countries	Status
1	Guenter Langergraber Chair COST Action	Implementing nature-based solutions for creating a resourceful circular city (Introductory paper)	8	5	Revised version submitted
2	David Pearlmutter WG1 Chair	Enhancing the circular economy with nature-based solutions in the built urban environment: Green building materials, systems and sites (WG1 review)	19	11	Revised version submitted
3	Volkan Oral WG2 Chair	State of the Art of Implementing Nature Based Solutions for Urban Water Utilization Towards Resourceful Circular Cities (WG2 review)	21	13	Revised version submitted
4	Johannes Kisser WG3 Chair	A review of nature-based solutions for resource recovery in cities (WG3 review)	23	16	Accepted
5	Siv Lene Skar WG4 Chair	Urban agriculture as an innovative mechanism to secure cities a sustainable and healthy development in the future (WG4 review)	16	11	Accepted
6	Evina Katsou WG5 Chair	Transformation Tools Enabling the Implementation of Nature-based Solutions for Creating a Resourceful Circular City (WG5 review)	25	16	Accepted

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1. Introductory paper

Implementing nature-based solutions for creating a resourceful circular city

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Abstract

Resource depletion, climate change and degradation of ecosystems are challenges faced by cities worldwide and will increase if cities do not adapt. In order to tackle those challenges, it is necessary to transform our cities into sustainable systems using a holistic approach. One element in achieving this transition is the implementation of nature-based solutions (NBS). NBS can provide a range of ecosystem services beneficial for the urban biosphere such as regulation of micro-climates, flood prevention, water treatment, food provision and more. However, most NBS are implemented serving only one single purpose. Adopting the concept of circular economy by combining different types of services and returning resources to the city, would increase the benefits gained for urban areas. The COST Action Circular City aims to establish a network testing the hypothesis that: "*A circular flow system that implements NBS for managing nutrients and resources within the urban biosphere will lead to a resilient, sustainable and healthy urban environment*". In this paper we introduce the COST Action Circular City by describing its main objectives and aims. The paper also serves as introduction to the review papers of the Action's five Working Groups in this Special Issue.

Keywords

Blue-green infrastructure, circular economy, nature-based solutions, resourceful cities.

1.1. Introduction

Cities worldwide are facing a number of challenges including resource depletion, climate change and degradation of ecosystems. If cities do not adapt their current infrastructure and resource management, they will not be able to cope with these challenges. Nature-Based Solutions (NBS) or Green Infrastructure (GI) solutions are one element that can help to achieve this transition. NBS and GI can provide mutual ecosystem services such as regulation of micro-climates, flood prevention, water treatment and food provision which are beneficial for the urban environment. To date, implementation of NBS focusses most of the time on achieving only one ecosystem service. The benefits gained for urban areas could be increased if the concept of circular economy is adopted by NBS achieving different ecosystem services and returning resources to the city.

The aim of the European Union funded COST (COoperation in Science and Technology) Action Circular City is to build an interdisciplinary platform for connecting city planners, architects, system designers, circular economists, engineers and researchers from social and natural sciences that develop systems for circular management of resources in cities. Such systems would allow cities to cope with the global challenges of resource depletion as a consequence of increasing pollution and climate change. In this COST Action, the definition of a common language and understanding across disciplines are seen as crucial success factor, while Circular Economy (CE) concepts are seen as key approach and NBS or GI solutions are seen as core elements of the toolbox.

The COST Action aims to encourage collaboration and research to test the hypothesis that *"A circular flow system that implements NBS for managing nutrients and resources within the urban biosphere will lead to a resilient, sustainable and healthy urban environment"*. The Action tests this hypothesis in five domains: built environment, urban water, resource recovery, urban farming, and society, with particular focus on their integration to provide solutions for circular cities. It is structured according to the five domains in five Working Groups (WGs).

In this paper, we firstly define the challenge and then describe the main objectives of the COST Action Circular City as well as its structure. As starting point for the common language required, we provide key definitions that we use in the Action and, additionally, we introduce the Action's five WGs as introduction to the WG's review papers that are also part of this Special Issue.

1.2. The challenge

Our world is approaching a situation where vital resources are peaking e.g., oil, phosphorous, water, space, while at the same time generation of pollution is growing and climate change is proceeding. Present day's infrastructure and resource management systems are not capable of dealing with this challenge. In fact, their linearity (import-use-dispose) and consumption oriented paradigm is one of the major causes for the problems that we are facing. Continuing the 'business-as-usual' approach to resources, management will cause severe problems even in areas where such problems may seem negligible at present. Wealth and well-being of coming generations will depend on our ability to adapt our economies to this challenge in the finite world we are living in. Transforming today's cities into sustainable and resilience cities is one of the main adaptations that will be necessary. A holistic approach looking at cities from a system's perspective is needed to achieve this goal.

NBS and especially GI are introduced in the urban landscape to cope with challenges cities are facing. These challenges are urban heat islands, flooding events, treatment of waste- and runoff waters from different origins and food provision. According to the EU Biodiversity Strategy to 2020, GI could encourage a better use of nature-based approaches to tackle climate change and to improve resource efficiency, for instance through more integrated spatial planning and development of multifunctional zones that are capable of delivering benefits to biodiversity, the land owner and society at large. NBS offer a range of ecosystem services beneficial for the environment. However, NBS are often built without considering their multifunctionality. Thus, NBS only fulfil a single function with little consideration of their recovery potential of waste and water, or their positive symbiosis with other systems. NBS can provide an array of valuable services, such as clean water production, nutrient recovery, heavy metals retention and recovery as well as production of a broad range of plant-based materials. NBS are ideally energy and resource-efficient, and resilient to change, but to be successful they must be adapted to local conditions (EC, 2015a). In order to achieve successful implementation and dissemination of NBS, there is a need to raise awareness on NBS, since the concept of NBS still remains vague or unknown to the larger public (Nesshöver et al., 2017). Furthermore, services from NBS are often considered public goods, and their economic value is often not recognised by the markets. Consequently, their true economic worth is not reflected in society's decision-making and accounts (Kinzig et al., 2011).

The CE philosophy based on the 3Rs: Reduce, Reuse and Recover (EC, 2014; Winans et al., 2017), has emerged as an alternative to the wastefulness of the current linear *"take-make-use-dispose"* practices of urban areas. The principle of CE is to create a closed loop for each natural or man-made product by transforming the linear resource flow into a circular flow. It targets all kinds of industrial processes and products. Regarding the urban environment, the scale of thinking is rather global in order to address the urban metabolism as a whole, and create not only specific CE systems, but also an overall resource management system for the urban biosphere. NBS can contribute to this on a local level as they can be easily adapted and operated decentralised where the highest demand occurs. The highest benefits of NBS besides their technical initial purposes is the influence on urban micro-climate and recreation purposes for the inhabitants.

As stated by the European Commission (EC, 2015a, 2015b), CE and NBS are major parts of future developments in order to provide resources and a life-friendly environment especially but not only in urban areas. This COST Action intends to establish an interdisciplinary environment for researchers and practitioners to counter hazardous impacts of mass urbanisation and linear flows by implementing NBS. The various benefits of implementing NBS now, as described by the European Commission (2015b) can be further enhanced by the approach proposed in this COST Action. NBS contribute to sustainable urbanisation, climate change adaptation and mitigation as well as risk management and resilience. When materials become waste, the net loss of natural resources is increasing leading to the depletion of our natural capital. In addition to reducing the production and spread of hazardous materials, NBS will have additional benefits on type and method of resource use, reuse and recycling based on CE principles for the urban biosphere. This COST Action develops combined approaches to implement NBS within a CE environment enhancing the benefits provided by the implementation of NBS and increasing the reuse of "secondary raw materials" such as organic matter, nutrients and water. This approach also represents one of the key elements for the implementation of CE (EC, 2015a).

1.2.1. State-of-the-art

While only occupying 2% of the earth's landscape, the urban environment consumes around 80% of the energy generated worldwide, while producing 75% of the global CO_2 emissions. The global material consumption has grown eight fold over the past 100 years and is expected to have tripled by 2050 (Krausmann et al., 2009; UNEP, 2011; Koop and van Leeuwen, 2017). With 75% of global natural resources being consumed in cities, an increasing scarcity of resources such as fertile land including nutrients, clean water and air as well as raw materials (metals, wood and plastics) is expected (EMF, 2012). This generates more and more pressure on rural areas and natural ecosystems to secure the supply of water, energy, food as well as the removal of waste.

City managers and politicians are challenged to find new ways to meet these demands within their municipalities. With the concept of CE, all kinds of loops in the production chain, waste disposal and water reuse can be closed. CE adapted for cities can include the following principles: regenerate, share, optimize, loop, virtualize and exchange goods and energy (EMF, 2015). In this context, different points of view concerning CE exist (EMF, 2016), which are mainly dependent on the goals and mostly influenced by the involved stakeholders, and specifically addressing different materials. The overall approach stays the same, namely neglecting a linear resource flow where at the end of the chain is the disposal by closing the loop through reusing and recycling resources within a defined system. The European Commission has adopted an ambitious CE package, which encourages actions that contribute to "closing the loop" of product lifecycles through greater recycling and reuse, with significant environmental and economic benefits (European Commission, 2015b).

Despite technological innovation and improved public awareness of the environmental impacts, the increasing trend of urbanisation will make the 50% reduction in CO_2 emission by 2050 a far-fetched target. On the other hand, present day food, energy and water systems are advancing technologically, but achieving poor results when addressing the global challenges due to insufficient communication and cross-sectorial collaboration. The challenge of urban resilience is not a single sector or discipline solution. It therefore seems crucial to invest on finding interdisciplinary solutions addressing the urban metabolism as a whole pushing the frontier of the urban biosphere (Dong et al., 2016; Fujii et al., 2016; Kennedy et al., 2009). The benefits of NBS and GI are demonstrated in several EU funded projects and COST Actions (e.g. COST Actions on the Green Infrastructure approach, FP1204, and on Urban Allotment Gardens, TU1201). According to the European Commission (2015a), the emerging NBS are "living solutions inspired by, continuously supported by and using nature, which are designed to address various societal challenges in a resource-efficient and adaptable manner and to provide simultaneously economic, social, and environmental benefits". Therefore, NBS has become a plausible concept to address the urban environmental challenges that arise as a city rapidly urbanizes (EC, 2015a; Maes and Jacobs, 2017).

The concept of NBS builds on and supports other closely related concepts such as the ecosystem approach, which promotes the integrated management of land, water, and living resources as well as their conservation and sustainable use (Faivre et al., 2017; Eggermont et al., 2015). Moreover, the Ecosystem Services (ES) framework is used to highlight the benefits NBS provide in urban areas (Bolund and Hunhammar, 1999; Haase et al., 2014). These benefits include local climate regulation through air cooling (Stewart and Oke, 2012), mitigation of flood risks (Ozment et al., 2019), air pollution control (Yin et al., 2011; Gómez-Baggethun and Barton, 2013) and noise reduction (Bolund and Hunhammar, 1999), when implementing green spaces, parks, green roofs and green walls. Direct health benefits may include positive effects on mental and physical health through stress reduction, relaxation and general health enhancements when citizens reside in urban areas (Hartig et al., 2014; Völker and Kistemann, 2011). Finally, the presence of green and blue spaces provides the opportunity to experience nature and to enhance public ecological knowledge and awareness of nature conservation (Lundy and Wade, 2011).

Finally, an important and many times overlooked service of NBS for decreasing the ecological pressure from cities is the provision of food. Edible NBS or urban agriculture systems are crucial for closing the nutrient cycle. Safely extracted resources from domestic waste flows used for urban food production address some of the biggest challenges that we are facing today: reducing waste outputs from cities, preserving decreasing phosphorous reserves by utilizing phosphorus and nitrogen from wastewater, reducing food-related transportation distances and associated energy consumption and greenhouse gas emissions, and reducing the need for land and energy intensive food production systems. In addition, urban agriculture systems can have high levels of biodiversity, often exceeding that of other green spaces within the city, which has a positive effect on ecosystem services (Lin et al., 2015). Depending on the available space, different concepts of urban agriculture exist, ranging from traditional systems to vertical or underground farming as well as small decentralised systems like shared neighbourhood gardens (Bohn and Viljoen, 2010; Buehler and Junge, 2017; Thomaier et al., 2015). It has been shown that implementing different concepts can significantly increase the self-reliance of the cities (Grewal and Grewal, 2011; Säumel et al., 2019) whereby the results of Wielemaker et al. (2018) reveal that integration of urban sanitation and urban agriculture can maximize urban self-sufficiency.

The shift towards more circular and sustainable modes of production and consumption is driving a shift towards greater energy efficiency and a smaller carbon footprint. In a CE, raw materials are re-used and recycled; and new materials needed for the energy transition are produced more efficiently and sustainably. In turn, products are designed to be reusable, or to be easily repaired or disassembled, to facilitate remanufacturing and recycling (EPSC, 2019).

It is time to systematize the use of NBS and the CE approach to resources management in cities by introducing changes in our legislation, resources utilization concepts, technologies, economic valuation and last but not least revision of the society's values, which is a great challenge.

1.3. The COST Action Circular City

1.3.1. What is a COST Action?

COST (COoperation in Science and Technology – see www.cost.eu), the longest running European framework, is a unique platform where European researchers can jointly develop their ideas and initiatives across all scientific disciplines through the trans-European networking of nationally funded research (COST, 2019). COST activities are largely arranged as COST Actions. Calls for COST Actions are open, i.e. Actions can be submitted related to any scientific field.

A COST Action does not fund research. It is a science and technology network funded over a four-year duration. An Action is organised through a range of networking tools, which are performed for the purpose of supporting and ultimately achieving research coordination and capacity building objectives. Networking tools include meetings, workshops, conferences, training schools, short-term scientific missions (STSMs) and dissemination activities.

All COST activities have to be inclusive in terms of gender, age and geography. Special networking tools are available for underrepresented groups, e.g. Early Career Investigator or participants from less research-intensive countries, also referred to as Inclusiveness Target Countries.

Activities of COST Actions are coordinated by the Action Chair and Co-Chair supported by the Chairs and Co-Chairs of the Working Groups as well as the persons coordinating specific activities (e.g. STSMs and science communication). All decisions are made by the Action's Management Committee (MC). In the MC each participating COST country can nominate two representatives. Currently, 39 countries are participating in COST and thus are COST countries. In general, activities of Actions are open to all persons working in COST countries.

For more details about COST Actions the reader is referred to the COST website at https://www.cost.eu.

1.3.2. Objectives & Outputs

The COST Action CA17133 Circular City provides a network for researches and practitioners from different fields: (waste-) water engineering, agronomy, urban agriculture, urban planning, architecture, energy, IT, etc. linking their fields to close knowledge gaps within the systems and scales looked at. Within this COST Action, a large number of people will be connected supporting each other and work together on finding interdisciplinary solutions to cope with the above-mentioned challenges.

The Action's objectives and outputs have been defined in its MoU. Objectives are reached with the Action's research coordination and capacity building activities, respectively. The methodology how the outputs will be delivered was not set at the beginning. Developing a common methodology is an essential part of the work in this interdisciplinary Action.

The Action's main research coordination objectives are:

- Use an interdisciplinary approach applied by the different working groups to map occurring resources within the urban biosphere, especially provided by NBS systems.
- Develop appropriate communication methods, promoting resource recovery for consumers and built up public awareness on the benefits of a closing the loop approach.
- Identify, analyse and report the existing state of the art of NBS implementations in the urban landscape by involving stakeholders such as city officials, urban planners and engineers.
- Identify and address regulatory, governance, financial and legal drivers and barriers for NBS implementation and use of recovered resources, and support institutional change to better regulatory governance.

The Action's main capacity building objectives are:

- Widen the field of knowledge within each working group by incorporating a joint research approach.
- Involvement of special target groups such as city official, urban planners and engineers, gender equality and involvement of underrepresented /less research-intensive countries.
- Training of Early Career Investigators (ECI) and PhD students, in the implementation of interdisciplinary approaches concerning resource recovery, reuse and coordinating resource streams within the urban landscape when developing structural measures using NBS.

A full list of objectives can be found in the Action's Memorandum of Understanding (CA17133, 2018)

The Action's main outputs are (CA17133, 2018):

- a review on the state-of-the-art and existing case studies,
- a catalogue of technologies for providing/recovering resources with NBS within each WG,
- a description of possible resource input provided from NBS systems,
- scientific publications including case studies, and
- a guideline on combined NBS and CE possibilities within the urban environment

1.3.3. Working Groups

The COST Action Circular Cities comprises five Working Groups. Each WG is led by a Chair and Co-Chairs elected by the MC of the Action. Besides members of the MC, also other persons can join the WGs. Usually persons are members in only one WG for the whole duration of the Action. However, this is flexible as some persons prefer to work in two or more WGs and/or switch WGs.

Even though each WG in the Circular City Action is focusing on a different subarea of the urban metabolism, it is necessary to connect the findings to define the potentials of embedding NBS in a CE. In order to achieve good interconnection between the individual WGs (Figure 1), the tasks and activities especially of the technology focused WGs are similar.

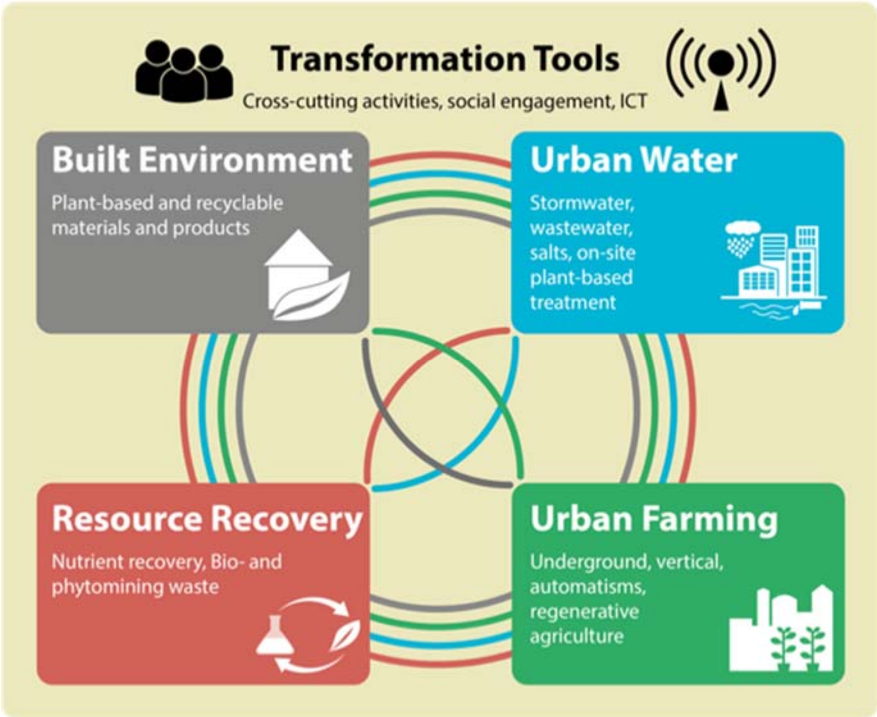

Figure 1: The Action's Working Groups and their interrelations (CA17133, 2018).

The Action's five WGs are as follows:

- *WG1 Built environment*: The built environment puts the main focus on the natural environment and its role in transforming to a CE system (Pomponi and Moncaster, 2016). Within this working group, the NBS-CE aspect is investigated on building and settlement level with the main focus on vegetated building materials and resources to be obtained from the corresponding NBS. WG1 defines available resource streams connected to NBS within the built environment. Moreover, the aim is to identify best-practise case studies, monitor resource loops and investigate possible available resources provided by relevant NBS proposed by other WGs.
- *WG2 Sustainable urban water utilisation*: This working group investigates the implementation of a save and functional water cycle within the urban biosphere, where water is defined as a resource, nutrients can be harvested from wastewater, heavy metal adsorbed by filter materials contributing to phytomining and the treated water looped back for irrigation, sanitation and also recreational purposes. The resource recovery methods are established in WG3. WG2 critically appraises the established centralised infrastructure for water, furthermore, defines available resources within the water flow, performs risk assessment on urban water and evaluates NBS for storm water management and waste water treatment.
- *WG3 Resource recovery*: A significant portion of resources is lost when passing through the urban biosphere. The implemented NBS for mitigation or treatment purposes shall become sources for a variety of resources to be harvested, used, reused and recycled within the urban environment. Therefore, possible sources and implementation strategies within the urban biosphere are investigated. WG3 identifies, appraises and assesses the available resources in the urban context, like waste- or runoff water, liquid and solid waste streams, materials from the other WGs, urban pollutants etc. Furthermore, the aim is to combine innovative NBS applications such as regenerative biological systems, phyto- or bio-mining, bio-filtration. The

outcome will be the creation of new areas for urban farming, waste treatment, run-off treatment and so on.

- *WG4 Urban Farming*: The WG on Urban Farming focuses on the integration of resources from other working groups (water, nutrients…) into urban farming systems as well as on the resources provided through urban farming for further use in other WGs. The WG will further investigate different urban farming systems especially developed for dense urban areas (e.g. underground farming, vertical and rooftop farming) and their potential for symbiosis with other WGs (e.g.: urban farming with wastewater, urban farming on formally contaminated soil after phytomining was carried out, etc.). While the main purpose of urban farming is food production within a city, the Action pays close attention to other resources available from urban farming, usually considered waste. Furthermore, the evaluated systems will consider the amount of resources available from other WGs.
- *WG5 Transformation tools*: WG5 coordinates and leads the interdisciplinary activities between the WGs. For this, the 'Circular City Cell' was established. The 'Cell' is composed of members from all WGs with specified tasks aimed at facilitating cross-group communication and research. The first objective of WG5 is to investigate performance-based assessment tools for measuring the impact of resource recovery and reuse cycles as well as reviewing ICT tools to facilitate the implementation of NBS. Moreover, associated barriers to the implementation of NBS on legal and stakeholder level are identified. The second objective is to develop a mechanism to translate the insights of the first objective into simplified tools and information for stakeholders. The third objective of WG5 is to establish public relations strategies and approaches to provide stakeholders with accurate, timely and satisfactory information, with the intention to maximise public engagement. Furthermore, WG5 aims promote effective knowledge dissemination and public engagement, and to suggest methods to monitor and interpret citizens' well-being and consumption trends (socio-economic preferences).

1.3.4. Definitions

Already during the initial discussions when setting up the Action it became clear that several terminologies are used differently in the various fields involved in the Action. To be able to communicate with a common language, the Action defined the following terms: Nature-Based Solutions, Circular Economy, Ecosystem Services, Circular City, and micro/meso/macro-scale (Table 1).

Table 1: Definition of relevant terms in the COST Action Circular City.

Term	Definition
Nature-Based Solutions	NBS are defined as concepts that bring nature into cities and those that are derived from nature. NBS 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. 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 discussed in WG3 Resource Recovery), as they may be needed for supporting and enhancing the performance of NBS.
Ecosystem Services	Ecosystem services are the benefits people obtain from ecosystems. These ecosystem services have strong links to human well-being.
Circular Economy	CE is defined as an economic system that aims at minimising waste and making the most of resources. In a circular system resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing energy and material loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling.
Circular City	A Circular City is where we apply the concepts of CE, i.e. we manage waste, commodities and energy in smarter and more efficient ways. A Circular City results in less pressure on our environment, new business models, innovative designs and new alliances and cooperation between different stakeholders.
Micro/meso/macro-scale	In the Action Circular City - *Micro-scale* relates to household level, - *Meso-scale* relates to district level, and - *Macro-scale* relates to city level or above. When referring to the Built Environment (WG1) - *Micro-scale* relates to green material, - *Meso-scale* relates to green buildings, whereas - *Macro-scale* relates to green sites, which are parts of the city or surrounding areas of buildings.

Nature-Based Solutions:

The Action's definition of NBS is based on definitions of the EU that refer to solutions that are inspired and supported by nature (EC, 2015a) and solutions that are designed to bring more nature and natural features and processes to cities (EC, 2015c). These EU definitions were amended by incorporating solutions that use or mimic natural processes to enhance water availability, improve water quality, and reduce risks associated with water-related disasters and climate change (UNESCO, 2018) and ideas from the three criteria for NBS as suggested by Albers et al. (2017): First, NBS need to provide simultaneous benefits for society, the economy and nature; Second, the term should be understood to represent a transdisciplinary umbrella; and third, a NBS needs to be introduced gradually.

Ecosystem Services

Ecosystem services are the many and varied benefits that humans freely gain from the natural environment and from properly functioning ecosystems. Ecosystem services can be grouped into four broad categories: *provisioning*, such as the production of food and water; *regulating*, such as the control of climate and disease; *supporting*, such as nutrient cycles and oxygen production; and *cultural*, such as spiritual and recreational benefits (MAE, 2005). These ecosystems services support achieving the constituents of well-being such as security, basic material for good life, health, good social relations, and freedom of choice and action (MAE, 2005). NBS and treatment wetlands in cities allow to achieve multiple purposes and ecosystem services (Masi et al., 2018)

Circular Economy

The Action's definition of CE is based on the 3Rs; Reduce, Reuse and Recover. CE is an economic system aimed at minimising waste and making the most of resources (EMF, 2016, 2017). In a circular system resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing energy and material loops; this can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling (Geissdoerfer et al., 2017). This regenerative approach is in contrast to the traditional linear economy, which has a 'take, make, dispose' model of production.

Circular City

A Circular City is where we apply the concepts of CE, i.e. where we manage water, nutrients, commodities and energy in smarter and more efficient ways, so that minimal amount or no waste is produced. A circular city will result in less pressure on our environment, new business models, innovative designs and new alliances and cooperation between different sectors and stakeholders (Cities in Transition, 2019). Alongside the *UN Sustainable Development Goals (UN, 2015)* and climate objectives, the transition to a circular economy will support city leaders as they deliver against their priorities, which include housing, mobility, and economic development (EMF, 2017).

Micro/meso/macro-scale

A general definition of micro/meso/macro-scale was not possible. Most WGs use micro for household level, meso for district level, and macro for city level or above. When referring to buildings and the built environment (WG1), the definition did not fit and was amended to micro relating to green materials, meso relating to green buildings, and macro relating to green sites, which are parts of the city or surrounding areas of buildings.

1.4. This Special Issue

The members of this COST Action hold a broad knowledge about different aspects of CE, NBS and Circular Cities. Therefore, the first step of the Action is to review, make the knowledge accessible to the society and create synergies. These review finally results in the Action's first main output, i.e. the "review on the state-of-the-art and existing case studies".

For the review of the state-of-the-art in the Action's five WGs a common database is used as a starting point. This database comprises the available knowledge in the Action's network and includes information on 72 projects related to Circular City. Information on projects has been collected in the form of project ID cards from members of the COST Action and participants of the first Circular City workshop held in Vienna, Austria, from 14-16 February 2019.

Based on the information collected from the project ID cards, 29 out of the 72 projects are European funded and among these 29 projects, 16 are funded by European Union’s Horizon 2020 Research and

Innovation. Regarding the stage of the projects, 26 out of 72 are completed while, 11 projects are at an early stage of the project's development.

Among the 72 projects, 11 European and National projects are selected and presented. Table 2 provides an overview on the 11 projects, s some general information regarding their funding source, their duration and the projects' scale (according to the definition provided in Table 1, "In the Action Circular City"). Additionally, the projects' representatives were asked to identify the focus of their project based on the classification and allocation to the WGs of the Action.

Table 2: General information and allocation to WGs 1- 4 of 11 selected projects (EU H2020 = European Union's Horizon 2020 research and innovation).

Project title	Funding source	Time frame	Scale	WG 1 Built Environment	WG 2 Urban Water	WG 3 Resource Recovery	WG 4 Urban Farming
CITYFOOD	EU H2020	2018-2021	Macro	X	X	X	X
C2C-CC	European Commission	2017-2022	Macro		X		
EdiCitNet	EU H2020	2018-2023	Meso to macro	X	X	X	X
ESTIMUM	Luxembourg National Research Fund	2017-2019	Micro to macro	X	X		
HOUSEFUL	EU H2020	2018-2022	Micro	X	X	X	X
HYDROUSA	EU H2020	2018-2022	Macro			X	
Nature4Cities	EU H2020	2016-2020	Macro	X	X	X	X
Natural Water Retention Measures (NWRM)	European Commission	2013-2014	Macro		X		
proGIreg	EU H2020	2018-2023	Meso	X		X	X
Run4Life	EU H2020	2017-2021	Micro			X	
URBAN GreenUP	EU H2020	2017-2022	Micro to macro	X	X		

The review of the state-of-the-art in the Action's five WGs is looking at the experiences available among Action members from different angles and identify what has been done, what was successful, what were the challenges, etc. and identify bottlenecks / research questions as well as interlinkages between the WGs as basis for the future work in the Action. In the following, the content of the five WG state-of-the-art reviews is summarised:

- Pearlmutter et al. (2019) present the point of few of *WG1 Built environment*. NBS are discussed at three different levels: (i) green building materials; (ii) green building systems; and (iii) green building sites. Concepts of NBS and CE in the built environment are introduced and the impacts of urban development and the historical use of materials, systems and sites is examined. A series of case studies is presented illustrating the development and implementation of such solutions in recent years. Finally, policy instruments which can be leveraged to promote NBS and CE in the most effective manner are discussed.

- Oral et al. (2019) describe the *WG2 Sustainable urban water utilisation* perspective. NBS for urban water management from literature and case studies are presented and analysed. The paper identified three main challenges: i) flood and drought protection; ii) the water-food-energy nexus; and iii) water purification. It is shown that NBS provide additional benefits, such as improving water quality, increasing biodiversity, obtaining social co-benefits, improving urban microclimate, and the reduction of energy consumption by improving indoor climate. The conclusion of the paper is that NBS should be given a higher priority and should be preferred over conventional water infrastructure.
- Kisser et al. (2019) present the state-of-the-art review of *WG3 Resource recovery*. The focus of the review is on NBS as technologies that bring nature into cities and those that are derived from nature, provided they enable resource recovery. The findings presented are based on an extensive literature review, as well as on original results of ongoing and recent research and innovation projects across Europe. The focus of the review was on urban wastewater, industrial wastewater, municipal solid waste and gaseous effluents, and the recoverable products (e.g. nutrients, nanoparticles, and energy). The implications of source-separation of waste and end-of-pipe technologies vs. circularity by design are discussed. Finally, an assessment of the maturity of different resource recovery technologies (Technology Readiness Level) is carried out.
- Skar et al. (2019) show the *WG4 Urban Farming* review. The scope of urban agriculture is to establish food production sites within the city's sphere through building-integrated agriculture including concepts such as aquaponics, indoor agriculture, vertical farming, rooftop production, edible walls, as well as through urban farms, edible landscapes, school gardens and community gardens. This article describes some of the current aspects of the circular city debate where urban agriculture is pushing forward the development of material and resource cycling in cities.
- Katsou et al. (2019) present the state-of-the-art in *WG5 Transformation tools*. A combined appraisal of the latest literature and a survey of projects provides an overview of enabling tools, methodologies, and initiatives for public engagement. Additionally, links between facilitators and barriers with respect to existing policies and regulations, public awareness and engagement, and scientific and technological instruments are described. The most promising methods, physical and digital technologies that may lead the way to Sustainable Circular Cities are introduced. The paper provides useful insights for citizens, scientists, practitioners, investors, policy makers, and strategists to channel efforts on switching from a linear to a circular thinking for the future of cities.

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2. WG1 review paper

Enhancing the circular economy with nature-based solutions in the built urban environment: green building materials, systems and sites

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Abstract

The objective of this review paper is to survey the state-of-the-art on nature-based solutions (NBS) in the built environment, which can contribute to a circular economy (CE) and counter the negative impacts of urbanization through the provision of ecosystem services. NBS are discussed here at three different levels: (i) green building materials, including biocomposites with plant-based aggregates; (ii) green building systems, employed for the greening of buildings by incorporating vegetation in their envelope; and (iii) green building sites, emphasizing the value of vegetated open spaces and water-sensitive urban design. After introducing the central concepts of NBS and CE as they are

manifested in the built environment, we examine the impacts of urban development and the historical use of materials, systems and sites which can offer solutions to these problems. In the central section of the paper we present a series of case studies illustrating the development and implementation of such solutions in recent years. Finally, in a brief critical analysis we look at the ecosystem services and disservices provided by NBS in the built environment, and examine the policy instruments which can be leveraged to promote them in the most effective manner – facilitating the future transition to fully circular cities.

Keywords

Built environment, circular economy, nature-based solutions.

2.1. Introduction

As defined by Langergraber et al. (2019), nature-based solutions (NBS) are concepts that bring nature into cities – and in many cases this includes ideas for urban design that are inspired or derived from nature. Thus while NBS may be considered more generally as actions which protect, sustainably manage, and restore natural or modified ecosystems (IUCN 2019), the specific focus here is on the implementation of NBS within *urban* ecosystems.

Even within cities, NBS contribute to global objectives such as climate change mitigation and adaptation, and they have the potential to enhance human well-being, biodiversity and resource recovery. All of these goals find expression in the design of buildings and urban spaces, or what is commonly referred to as the "built environment." Over the last 15 years, in fact, the concept of NBS has come to encompass design solutions for contemporary landscapes and architecture, in which natural and living material – as well as policies, measures and actions promoting their use – are leveraged to meet specific societal challenges that are pervasive in the built environment.

One example of a societal challenge that may addressed using NBS is the urban heat island effect (UHI), by which temperatures in cities are increasingly higher than in surrounding areas – exacerbating heat stress for vulnerable urban populations. In temperate climates this risk is highest during the night time, and mainly indoors (Buchin et al. 2016). Among UHI countermeasures, urban green space is considered among the most effective for reducing air temperatures outdoors, but for addressing the indoor hazard it is most effective to apply measures at the building level – highlighting the fact that NBS must be implemented at a range of scales in order to deliver the optimum benefit.

The ubiquitous grey infrastructure in cities – consisting of impervious paving, buildings, and other structures – contributes as a whole to the worsening of the urban climate through a lack of resilience and flexibility. Thus the importance of urban green infrastructure (GI) is related to the amelioration of social stresses, which are intertwined with physical phenomena in cities. Contemporary issues related to grey infrastructure include its ageing and the need for maintenance, along with the worldwide recognition that conventional infrastructure solutions are often insufficient and ineffective. The inclusion of NBS in new and innovative strategies can address such issues such as water quality while simultaneously delivering additional benefits. These benefits are vital to promote aspects of sustainable development presented in a 2018 United Nations report which states that "…upscaling (of) NBS will be central to achieving the 2030 Agenda for Sustainable Development" (WWAP 2018).

Another important aspect when approaching contemporary urban systems is "circularity".

Circular economy (CE) is an evolving 'umbrella' concept embodying internal complexities and multiple definitions, but is defined here (Langergraber et al. 2019) as an economic system that aims at minimising waste and making the most of resources. In a circular system, resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing energy and material loops. According to Prieto-Sandoval et al. (2018), "this concept represents a change of paradigm in the way that human society is interrelated with nature and aims to prevent the depletion of resources and facilitate sustainable development through its implementation at the micro (enterprises and consumers), meso (economic agents integrated in symbiosis) and macro (city, regions and governments) levels. Attaining this circular model requires cyclical and regenerative environmental innovations in the way society legislates, produces and consumes."

Moreover, cities are composed of multiple overlapping infrastructure systems, while at the same time become the spaces where people develop social experiences and cultural values. Urban quality is a target for cities that are competing against each other to attract the most valuable and entrepreneurial citizens. A great number of theories, manifestos and city guidelines have been developed in cities of the world to promote new urban qualities and citizen wellbeing. Frederick Law Olmsted argued that "…the enjoyment of scenery employs the mind without fatigue and yet exercises it, tranquilizes it and yet enlivens it; and thus, through the influence of the mind over the body, gives the effect of refreshing rest and reinvigoration to the whole system" (Olmsted 1865).

Biophilia is the "innate human attraction to nature", and as a concept, it has been recognized for several decades by the scientific and design communities, and intuitively for hundreds of years by the population at large. Biophilic design is of growing interest within architectural theory and practice, due to published research showing that design which increases the exposure and direct connection of people with the natural world "can reduce stress, improve cognitive function and creativity, improve our well-being and expedite healing" (Browning et al. 2014). Social life and culture develop constantly in the city context and their relation to nature and new green infrastructure solutions is a very important goal for NBS.

Against this background, the aim of this review paper is to survey the state-of-the-art on integrating NBS in the built environment, which can counter the negative impacts of urbanization and contribute to a circular economy through the provision of ecosystem services. We approach this review at three scales of implementation, those of building *materials*, *systems*, and *sites* (Fig. 1) – which, as defined below, constitute the focus of the paper.

Green building materials are raw and processed nature-based materials used in the construction of the built environment. These materials are extracted from the biological cycle to serve technical purposes, and their production and processing should result in low environmental impacts in terms of measures such as embodied energy and carbon, water consumption and the use of harmful chemicals. Ideally, they make productive reuse of other resource streams to avoid detrimental by-products and competition with food production, and they guarantee a healthy working and living environment with respect to indoor air quality and climate. The material processing and construction techniques should ideally be such that nutrients can be safely returned to the ecosystem at the end of the use cycle of the building material.

Green building systems in this context are systems for the greening of buildings, and include components such as green roofs, facade greenery and living walls, house trees, and even building-integrated constructed wetlands. Green roofs are designed with either intensive or extensive planting: an intensive green roof is supplied with water and nutrients and its substrate is usually thicker than 0.25m, while an extensive green roof is not irrigated and has a much shallower substrate, usually 0.06-0.15m. Façade greenery consists of clingers or climbers rooting in soil or artificial substrates, directly attaching to the wall surface or covering the wall indirectly through support systems like trellises or ropes. Since the plants use other structures to develop, they do not have to invest in their own static apparatus – an evolutionary adaptation that often allows them to grow much faster than trees (e.g. *Fallopia baldshuanica* reaches up to 12 m in height in just one growing season).

Green building sites may be open spaces directly adjacent to buildings, typically within in the same property, or land parcels of small and medium scale (pocket parks, urban plazas, small community parks, elevated urban green promenades) that have a role in the blue-green (i.e. water and vegetation-based) network of the city. Green building sites are spaces for establishing nature in cities, enhancing biodiversity through blue-green infrastructure components, providing opportunities for biophilic design and promoting culture and social life through activities for diverse social and age groups. Ideally green building sites provide multiple ecosystem services, and embody resilient and regenerative ways to deal simultaneously with challenges ranging from climate change mitigation to the reduction of noise pollution. They may increase flood safety through integrated water sensitive urban design (WSUD) solutions, improve air quality, reuse site material while reducing construction waste, use construction materials that are permeable and sustainable, promote local economic systems, and maintain low life cycle impacts. The intent of NBS at the green building sites scale is to promote sustainability goals, outdoor comfort, healthy living environments and wellbeing in cities.

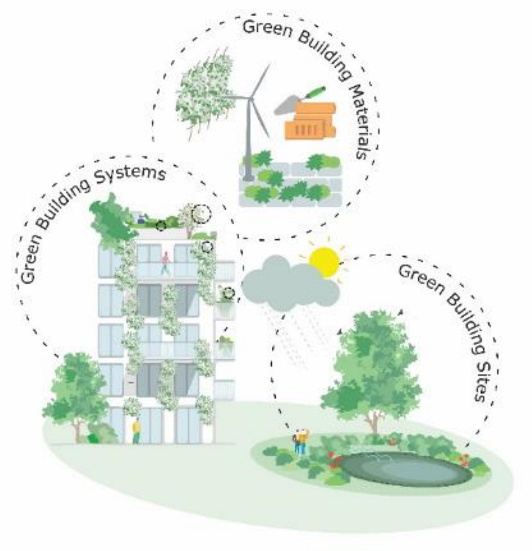

Figure 1: Three scales of NBS implementation in the built environment: green building materials, systems for the greening of buildings, and green urban sites. Illustration: Dimitra Theochari (unauthorized use is not permitted).

2.2. NBS in the built environment: problems and solutions

Meeting the challenges posed by urbanization and the growth of cities has a pivotal role to play in the transition of society to a circular economy (CE). These challenges derive from a wide variety of environmental impacts associated with the production of building materials, the operation of buildings and their allied systems, and the outdoor processes which take place within the built-up area (Elmquist et al. 2013). In this section we first summarize these impacts, and then survey the historical use of nature-based solutions that can be leveraged in the future to minimize their negative consequences.

2.2.1. Impacts of the built environment on people and natural systems

In Europe, energy use in residential and commercial buildings accounts for over 40% of the total end-use consumption (Enerdata 2012), making buildings the largest energy-consuming sector and a major emitter of greenhouse gases (GHG). However, this proportion refers only to "operational" energy use, or that which is consumed for heating, cooling, ventilation, and otherwise making the building habitable and supporting the ongoing needs of its occupants. Additional energy consumption and related GHG emissions are attributable to the production of the building and its constituent materials, and to the characteristics of urban open spaces – in which microclimatic and other processes crucially influence the dependence of people on energy-intensive buildings and urban transport. Therefore, the design of the built environment has a determinative impact not only on the quality of contemporary urban life, but also on society's long-term contribution to anthropogenic climate change and natural resource depletion (Kabisch et al. 2017).

Building material production

Most modern building materials are produced using processes that rely heavily on non-renewable resources, generate large quantities of waste, and potentially create unhealthy surroundings. The most ubiquitous of these materials is concrete, which may be either cast on site or used to manufacture pre-cast elements like wall blocks, and whose key active ingredient is Portland cement. Cement has an extremely high level of embodied energy in its production, and is a major source of GHG emissions (Huberman et al. 2015). This is because vast quantities of carbon dioxide are released to the atmosphere as part of the calcination process in which natural limestone and other raw materials are converted into clinker (the key ingredient in cement), and additional CO_2 is emitted due to the combustion of fossil fuel for producing the required temperature of approximately 1,500^{o}C. Because of such high-temperature production processes, many other modern materials have high embodied energy as well. These include the reinforcing used in structural concrete (especially when it is virgin steel produced from iron ore, rather than recycled from scrap), and even materials that are increasingly employed for thermal energy efficiency – such as aluminium and glass for high-performance windows, and petrochemical-based plastics such as expanded polystyrene for thermal insulation. Beyond embodied energy and carbon emissions, a host of direct and indirect offsite environmental impacts (such as air pollution and water contamination) are also incurred through the extraction of minerals from mines and quarries, and the long-distance transport of both raw materials and finished products.

The building and its operational systems

Buildings provide people with shelter from cold, heat, wind and precipitation, but also have negative impacts on organisms and ecosystems. Among the direct impacts are the reduction of vegetation and disconnection of habitats on the ground, as buildings seal the soil and thus disrupt the cycles of water, gases, nutrients and energy. On building roofs, rainwater is concentrated in volume and time, and about 85% is typically directed to drainage where it infiltrates directly into the ground or into sewers – bypassing soils, plants and the atmosphere. Buildings impact the urban surface roughness and turbulent exchanges of heat and pollutants, often trapping them in streets and other occupied spaces. Compared to a vegetated surface, buildings also increase the absorptive surface and the heat storage capacity by accumulation of high density, high heat capacity materials, which leads to longwave radiation emission during the night and the formation of urban heat islands – contributing to heat stress both indoors and outdoors. In cold northern climates, densely packed buildings can block sunlight to an undesirable extent in terms of both health and potential passive solar heating.

Because urban populations spend the large majority of their time indoors, their consumption of water, materials and energy – and their production of wastewater, waste and excess (anthropogenic) heat – are concentrated within buildings. Biological primary production is reduced to a minimum, as food is imported, processed and consumed, with residues and waste flushed into the sewer system – again bypassing the soil (where these organic materials are usually decomposed and mineralized) and the vegetation (which is usually taking up the corresponding nutrients). Heating and cooling in homes, businesses and industry consume around half of the energy produced in the EU (Enerdata 2012), and buildings are projected to remain the largest energy-use sector worldwide, even under future decarbonisation scenarios (US EIA 2017).

Outdoor processes in building sites

Urban spaces, typically covered by hard paving using materials like concrete and asphalt, can create environmental problems both within and beyond their boundaries. Without shade from trees, such spaces exacerbate thermally stressful microclimatic conditions on hot days and discourage pedestrian activity – which can in turn increase the reliance of city dwellers on air-conditioned vehicles and indoor spaces. When the albedo of unplanted ground surfaces is low, their surface temperature may reach extreme levels, and when it is high they expose users to reflected solar radiation which increases visual as well as thermal stress. Hydrologically, large areas of impervious paving contribute to surface runoff that may lead to soil erosion, impaired water quality and the risk of flooding.

These sites also diminish biodiversity, by creating a harsh environment for wildlife. The strongest impact comes from direct habitat destruction, when existing green spaces are replaced by buildings and roads. Remaining habitats, as well as newly built ones, also face challenges, mostly related to habitat fragmentation. Green spaces in cities can be viewed as islands isolated by a hostile environment, and thus species present must cope with different abiotic pressures, e.g. from increased air pollution (mostly from vehicles), altered microclimate (related to the urban heat-island effect) and isolation (which limits species dispersion between green spaces). Also, the biotic interactions between species are affected due to the presence of exotic and invasive species, and the prevalence of disturbances stemming from human activities, such as noise pollution.

2.2.2. *Historical overview of NBS in the built environment*

Traditional building materials and techniques

The use of “nature-based solutions” in the built environment is not a new phenomenon, as builders throughout history have employed materials and techniques enabled by the natural surroundings. Indigenous architecture around the world is characterized by buildings that were constructed from local materials and often displayed a remarkable unity with their environment (Blaser 1982). By using locally available resources in ways that respond to local conditions, traditional building practice has led to the evolution of distinct regional building types. Prominent examples vary from domed igloos built of ice and snow in arctic regions to solid earth construction (cob, rammed earth, mud bricks) without an interior skeleton structure, as can be seen in adobe Pueblos of the arid American southwest (Lehner 2016). Natural stone is among the most important building materials due to its strength and durability, either forming whole huts (Italian Trulli or Bories in the Provence) or building up houses with thick stone walls supporting a turf roof with living grass sod (Blaser 1982). As detailed below, living plant material was also used to form ficus tree bridges in India (Rodgers 2019).

More common than living plant material is the use of harvested material, in a wide range of construction types from the compact wooden architecture of Europe to light bamboo piles in Asia. Tipis of the Great Plains and yurts of Central Asia exemplify skeleton structures of wood or other plant material covered by tensile fabrics of plant-fiber or animal skins. The Hawaiian hale consists of a more complex skeleton structure system, containing a ridge purlin and different junctions, covered with plant leaves. In the Nile Valley of Egypt, typical dwellings were constructed using an inner structure made of wooden poles, reeds or wickerwork, covered by a layer of mud. Another plant-based material typical for eastern construction is paper, used for Japanese shoji doors or fusuma screens (Brown 2012).

The use of wood in construction traditionally reflects the proximity of forests and the availability of tree species with given properties. In areas such as northern Europe that are rich in trees with hard and solid stems, heavy timber walls and snow-bearing pitched roofs with wooden planks have been historically pervasive – though today they have largely disappeared from many regions due to the high price of wood. In areas where forest trees yield thinner and shorter trunks, there is a more common use of lighter wood-frame walls filled with other materials such as brick, and where timber is scarce, soil is often used as a construction material, together with light wood and reed. In stony-karst (e.g. Mediterranean coast and mountain) areas, stone construction is dominant – and in 2018 the art of dry-stone walling in countries such as France, Greece, Italy, Croatia and Spain was acknowledged by UNESCO to represent an intangible contribution to the cultural heritage of humanity.

A number of properties commonly found in indigenous architecture can be instructive for the future implementation of NBS (see overview of traditional materials in Table 1):

- Material is sourced from local vegetation or geological deposits (Heringer 2012).
- Reliance on non-renewable energy resources is low (Heringer 2012).
- Building form is thermally and structurally adapted to climate (Pearlmutter 2007).
- Durability is enhanced by regular maintenance (Georgi-Thomas and Zeumer 2012).
- Buildings are simple in construction and the materials are recyclable and compatible with biological cycles (Sauer 2012).

Building greening systems that are integrated with user lifestyles

Vegetation has always played an important role in the direct surrounding of houses. Living green plants symbolize life, health and prosperity – and have provided countless advantages to the inhabitants.

Trees planted directly next to the house are a regular feature of settlements in Europe (Wieland 1983). In central Europe, common species include Oak (*Quercus spp.*), Lime (*Tilia platyphyllos*), Ash (*Fraxinus excelsior*), Pear (*Pyrus*) and Apple (*Malus domestica*). In southern Europe *Magnolia spec.*, *Acer*, *Olea europaea*, and Palm trees (*Palmae*) have been common, as has *Platanus* in Western Europe. Trees have been appreciated for their aesthetic value as they indicate the seasons by flowers and colorful foliage. They also structure the direct surrounding of houses through shadow and light patterns, and deciduous trees selectively cast shadow in the summer and let the light pass during winter. Different species provide fruit, pharmaceuticals, fodder, and valuable wood, and attract insects for pollination. Trees have often carried a high cultural and mystic-religious importance as well. Nowadays, in spectacular cases such as the "Hundertwasser Haus" in Vienna (Austria) or the "Bosco Verticale" in Milano (Italy) trees are brought into and onto houses (Fig. 2). At the same time, the appreciation for ordinary, traditional house trees and street trees is decreasing, as dwellers think they have less need for the trees' services. The work in gardens and the surroundings of houses has been outsourced (like in the Bosco Verticale) and for municipalities, costs caused by leaf fall and liability questions seem to be most important aspects. This development together with pests and diseases like ash dieback, Dutch elm disease, or the *Ceratocystis platani* and Massaria disease of *Platanus* species are decreasing the number of house and street trees across Europe.

Table 1: Traditional building materials and their relevant properties for implementation of NBS.

Source	Material	Uses	Recyclable / reusable	Renewable	Environmental impact
Animals	wool/hair	blankets, carpets, textiles for insulation and shading	can be reused/reshaped or be used as an additive	yes (grows on animals)	CO_2 – impact of animal production (but could be a side product of food production)
		additive in clay or concrete	not reusable because bound in material		
	leather/pelt	tipi/yurt coverage	depending on process of dressing	yes	
	dung	floor, ground material	can be composted or burned	yes (animal waste product)	
		additive in clay or concrete	once dried out not easy to reuse, but can be returned to soil		
Plants	living plant material	sod for roofing	can be composted or burned at end of life	yes	binding of CO_2, habitat function
		climbers/clingers/creepers for bridges & sunscreens			
	wood	large-dimension timber & poles for primary structure	can be reused/reshaped repeatedly if not chemically treated, and composted or burned at end of life	yes, but careful management needed	binding of CO_2 during growth phase/harvesting, transport and production process creates positive or negative energy balance
		boards and planks			
		scantling, smaller pieces, shingles		yes	
	cork/bark	insulation material, flooring	can be reused or recycled	yes, but careful management needed	
	bamboo	roof structure, walls, fences, decoration	yes, but usually weak after initial use, can be composted or burned	yes, rapidly	
	rush, straw, thatch	roofs & ropes	can be composted	yes, rapidly	
	hemp	thermal insulation	yes	yes	
	paper	walls and screens	can be reused or recycled	yes	water/energy demand depending on production process, various chemicals added
		wallpaper	no (sticky glue on it)	partly	
Earth	water	icebuildings	can be reused or recycled	no	low
		component in clay or concrete	no		moderate?
	mud/clay	walls, floors, stoves	once dried out not easy to reuse, but can be returned to soil		low
		bricks	after firing not easily reusable, but can be returned to soil		average, depending on energy resource for firing
		tiles (glazed material)	reusable but not easily recyclable		depending on energy resource for firing and glazing
	stone	plaster	can be reused, recycled as gravel		depending on mining process and transport
		walls	can be reused, recycled as gravel		
		gravel	can be recycled in concrete		
	sand	glass	can be recycled		depending on mining process, transport and energy resource for production
	metal	various products	can be reused or recycled		
	lime	paint	can be returned to soil with other products		
	opus cementitum (lime and sand)	walls, floors, roofs	can be recycled in concrete		

Façade greening is the melding of the artificial constructed and the naturally grown. There are very old examples for climbers and vines which were used to green buildings like the legendary hanging gardens of Semiramis and the shade creating wine–pergolas of Roman villas (Gothein 1926). Useful climbers and vines might have always been brought near houses and might have greened buildings and walls. Hedera helix is one of the most prominent examples, described in antiquity by Hippocrates of Kos (460-370 BC) and Pliny the Elder (23-79 AD) and in historical times as well (Turner 1538). In central Europe it has been used as a garden plant at least from the middle of the 16th century, and has been appreciated for its pharmaceutical potential. In the 18th century, the German polymath Goethe introduced climbers (vine stocks and ivy) to the upper class as part of garden and building art. There is a long experience with indirect façade greening using trellises or pergolas to support vines (e.g. Vitis vinifera), and with direct façade greening using plants that have adventitious roots like Hedera helix or climbing roots with adhesive pads such as Parthenocissus tricuspedata. While vines and climbers have long been associated with building damage and attraction of pests, a detailed study (Schloesser 2003) showed that most inhabitants do have a positive attitude toward façade greening. It remains unclear why façade greening, given its aesthetical value, ecological importance and positive effects on mental and physical health (biophilia) are not more widespread in Europe. One initiative to remedy this is the I-BEST project currently in development by the University of Calabria, Italy: an innovative vegetated module for a green wall, which, by the integration with a rainwater harvesting system, allows for optimal urban water management and provides environmental and thermal benefits from a building scale to a city scale.

Figure 2: Examples of building integrated trees. Left: gardeners in front of Bosco Verticale in Milano, Italy and right: the Hundertwasser Haus in Vienna, Austria (photos: Thomas Nehls)

Green roofs are as old as façade greening, dating back to the Gardens of Semiramis as well. Traditionally, green roofs took the form of either sloped roofs covered with grass sod, or more sophisticated and intensively used roof gardens (Shafique et al. 2018). Turf roofs constructed for their insulation value have been a central feature of vernacular architecture in Iceland (van Hoof and van Dijken 2008), Greenland and Scandinavia (Ahrendt 2007). Roof gardens were constructed in ancient Rome to celebrate luxury, in the Renaissance to demonstrate the humanistic ideas of the owners, in the Baroque to symbolize the artificial look of the garden, and in classicism the antique examples flourished again (Ahrendt 2007). During all these epochs, the roofing technology changed only slightly, with bitumen, lead and copper as the main sealing materials. Apart from the turf roof, the motivations for hanging gardens have been the need for more productive land in dense cities, and the prestige to own a roof garden which symbolized wealth and power. With the advent of reinforced concrete it became much easier to construct flat roofs, with Hennebique among the first to recognize and to put into practice the greening of flat concrete roofs in 1901 (Kind-Barkauskas et al. 2001).

Recently, there is an increasing interest in developing more cost-effective green roof design, to use alternative building materials for liners and substrates, to combine greened roofs with solar energy production, and to create multi-purpose recreational space (Figure 3). Several cities are following this trend, and the EU Research and Innovation policy agenda promotes re-naturing cities and territorial resilience for socially and environmentally responsible communities, through the integration of NBS (EU 2015). However, a city's vision for the promotion and use of green roofs varies with the particularities of each place. Given the sustainability of green roofs over their full life cycle, policies are needed that encourage their use through regulation or financial incentives (such as water or property fee reduction), conditional to a pre-defined sustainable development goal attainment. Setting up quality standards for green roofs is important to scale up this NBS, with the German and the Spanish green roof guidelines being good examples for such (FLL 2018; NTJ 11C 2012).

Figure 3: Example of cities sharing space with vegetation: Green roof at Praça de Lisboa, Porto, Portugal (photo: Cristina Calheiros)

Larger scale green topics in cities

Historic examples of NBS in city infrastructure are represented through food security systems in cities. There is a long culture of urban allotment gardens in European cities (Bell et al. 2016), as well as a history of guidelines that promote food production – for example in Athens, Greece. Here, in the development of the city after the 1960s there were guidelines for front-yards that allowed for the planting of two-three citrus trees, herb gardens and a small vegetable garden. Other examples include cultural landscape sites such as monasteries and cloisters in Europe, where herb gardens, vegetable gardens, orchards, vineyards and seed conservation banks were established and have contributed to food security in European towns for centuries, but also the establishment of cultural landscapes that protect the sloping banks of water reservoirs from erosion. The role of religious communities in protecting know-how regarding crop modification and soil fertility management practices is significant in Europe, but also around the world. Ancient precedents for integrated aquaculture include the chinampas of Mexico and the integrated rice paddy systems across parts of Asia, while what is today is defined as aquaponics may be traced to the lowland Maya, followed by the Aztecs, who raised plants on rafts on the surface of a lake in approximately 1,000 A.D. Polyculture farming systems are common in far eastern countries as well (http://www.fao.org/3/y5098e/y5098e06.htm). Another example of historic NBS in infrastructure are the living-root bridges in the northeast Indian state of Meghalaya (Lewin, 2012), constructed using the Ficus elastica tree and inspiring contemporary architects for techniques called "baubotanik" (Ludwig 2012). In a similar way, practices of river restoration and bank stabilisation of soil-bioengineering that have been implemented in the rivers and streams of the Alps in Switzerland and Austria for years are being expanded in the design of contemporary ecological rivers and streams in cities.

Bioretention systems, biofilters, raingardens as well as constructed wetlands are green infrastructure systems implemented on the ground level for infiltration of water from different sources such as direct precipitation, runoff water, and in special cases polluted water from combined sewer overflow (CSO). These systems are areas that are excavated and filled with specific media depending on the actual multipurpose functions addressed, which may include maximizing the local infiltration capacity, thereby reduce stormwater volumes and relief pressure from the sewer system, serving as a stand-alone drainage system, supporting vegetation growth and providing sufficient water (Roy-Poirier et al. 2010). The last function is of utmost importance, as GI can only provide its benefits when there is sufficient availability of water. An import aspect is thereby related to the pollution of the runoff water. Heavy metals (HM) from roof tops and street runoff can degrade the groundwater quality. To cope with this, filtration media are developed to serve as barriers and retain pollutants such as HM (Haile and Fuerhacker 2018).

2.3. Current practice: circular solution case studies

In the following, we present a series of case studies that demonstrate innovative approaches to the development and implementation of NBS in the built environment. The first is a research project on the development of alternative green building materials, and the second is a pilot project demonstrating a novel approach to edible green walls. The third is a multi-faceted experimental park combining a green roof demonstration with of a number of other NBS technologies, and the final case study is a built example of a green building site in which the focus is on water-sensitive urban design (WSUD). The tables in the Appendices provide extensive lists of green projects in particular countries, illustrating the scope of implementation of different types of NBS.

2.3.1. Development of biocomposite building materials in the Negev, Israel

Project Title: "Biocomposite Building Materials Based on Agricultural Waste" (Scientific Team: David Pearlmutter, Erez Gal, Yaakov Florentin, Shahar Oannou, Francesca Ugolini)

Location: Sede Boker campus of Ben Gurion University of the Negev, Israel (30°48'N, 34°48'E)

Years of Design and Construction: 2016-2018

Nature-based Solutions Services: green building materials, recycled agricultural waste

Biocomposite building materials can have a significantly lower environmental footprint than conventional lightweight concrete, as they incorporate plant-based lightweight aggregates in a protective matrix – and these plants can sequester significant amounts of carbon in their growing phase. By exploiting agricultural by-products to produce these alternative insulation materials, a further contribution is made towards reducing waste in a circular economy. At the same time, because these plant materials are concealed within an inert binder, they are not exposed to damage from fire, pests or rotting.

Experimental studies in the arid Negev Highlands of southern Israel were conducted to develop and test innovative biocomposite materials incorporating hemp shives and dried orange peels, respectively, as the insulating aggregate. As part of an ongoing life-cycle assessment, the thermal properties of each biocomposite were analyzed through lab testing and experiments using small test cells (1 x 1 x 0.6 m) with 20 cm thick walls.

Functionally-graded hemp-lime biocomposite

Hemp-lime (HL) biocomposites are typically non-load bearing wall materials made from the woody core of the hemp plant (a non-psychoactive variety of *Cannabis sativa L.*), which is dried, cut into "shives" and mixed with a lime binder. These lightweight insulating materials are non-toxic, reusable/recyclable and meet European fire and acoustic standards. Moreover, their production can be carbon "negative", as CO_2 sequestered during the hemp plant's growth outweighs the net release of carbon in the production of lime (which gradually reabsorbs CO_2 through carbonation). In addition, HL is considered a "breathable" material characterized by moisture buffering and improved indoor air quality. While the outer fibers of the hemp stalk are used for textiles and other products, its woody core comprises about 70% of the plant's weight and is usually treated as agricultural waste (Florentin et al. 2017; Ip and Miller 2012; Zampori et al. 2013).

In the first phase of the study, a life-cycle assessment of a homogenous HL biocomposite (450 kg m^{-3}) showed that the net carbon emissions of HL production are drastically reduced relative to a conventional building material with similar density and thermal properties, and that the magnitude of this reduction in embodied carbon is equivalent to about five years' worth of carbon emitted due to seasonal heating and cooling of a typical building (Florentin et al. 2017). The HL was also compared to a material combining internal thermal mass and external thermal insulation, which was better able to moderate the temperature fluctuations of a desert climate. However, because this variable density insulated concrete is based on cement and expanded polystyrene, it is very high in embodied energy and carbon. Thus the second phase of the study focused on the development and analysis of a variable density "Gradient Hemp-Lime" block (Fig. 4) which could significantly reduce operational as well as embodied energy and carbon emissions.

Figure 4. (left) Gradient HL cross section; and (right) gradient HL test cell before plastering and roof installation, with homogenous hemp-lime cast on the corners to prevent thermal bridges.

The optimal configurations for the heavy and light phases of the gradient block were identified through lab testing, which included measurements of the density, thermal conductivity and volumetric heat capacity, and compressive strength of a wide range of samples in which various hemp-lime-sand-water ratios were cast and vibrated to separate the layers and attain a density gradient: from heavy on the bottom to light on top. A test cell was built of identical blocks based on the preferred ratio and vibration time, with the heavy side inward.

Results comparing the thermal performance of the gradient HL test cell to that of conventional lightweight concrete (Fig. 5) show that during the early fall, the gradient hempcrete preforms better in terms of moderating indoor temperature fluctuations – maintaining a maximum temperature of 23°C, which is in the range of thermal comfort. Thus the newly developed variable density hemp-lime composite block is seen in a preliminary analysis to offer superior thermal performance when compared with conventional materials of the same thickness. Furthermore, the "gradient hemp-lime" shows considerable potential to substantially reduce the environmental impact of non-load bearing wall materials, especially in terms of CO_2 emissions, due to the carbon-negative bio-based aggregate made from the woody core of the hemp plant. Ongoing work, including a complete life cycle energy and carbon analysis, will provide further evidence of its potential as a sustainable material for the building industry.

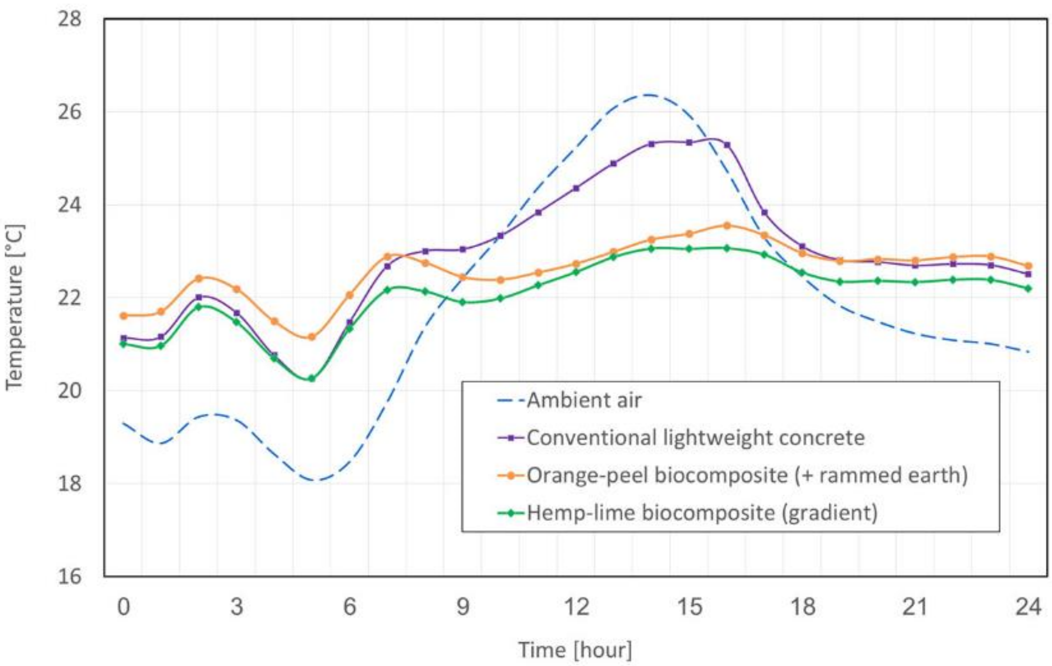

Figure 5. Internal air temperature of test cells with wall construction based on the gradient hemp-lime and orange-peel biocomposites, compared with conventional lightweight concrete (18 October 2018 at the Sede Boker campus).

Citrus waste bio-composite and rammed earth

An innovative bio-composite building material based on agricultural waste was developed using dried orange peel (OP) particles as a lightweight aggregate and clay as a binder. This insulating biocomposite was integrated in a double-layer wall system, with the inner layer consisting of rammed earth (RE) for thermal mass.

The potential of this green material stems from the fact that most industrial waste from citrus (estimated at 15 million tons per year globally) is created in the juice production process and much of it consists of orange peels (USDA 2014; Marin et al. 2007). While this waste material may be used to produce animal feed or natural fertilizer for agriculture (Beccali et al. 2009), it is clear that orange peels represent a sizable potential resource for new applications such as building materials. The fact that much of the resource is already concentrated in processing plants for juice production means that its collection could be far more efficient than for other types of agricultural waste. The second wall material, rammed earth, is based on a traditional method of construction with naturally low embodied energy (Venkatarama Reddy & Prasanna Kumar 2010).

In the initial phase of the study, samples of the OP bio-composite with different proportions of OP and clay binder were compared in order to identify the highest proportion of insulating OP that could be used without compromising the mechanical stability of the composite as an infill (non-load bearing) material (Fig. 6). The optimal configuration (with a density of 900 kg/m^3) was found to contain 46% OP and 52% clay by weight, with the small remainder consisting of Natural Hydraulic Lime (NHL) to minimize shrinkage. This proportion of insulating plant material is in agreement with general recommendations for hemp-lime mixtures as well. OP particle size fractions (from <1.2 to >4.7mm) and water content were also optimized.

Test cell measurements (see Fig. 5 above) showed that the orange-peel-rammed earth wall is able to moderate internal temperatures to a greater extent than lightweight concrete, and to nearly the same extent as the graded hemp-lime biocomposite. This indicates that the combination of external biocomposite insulation and internal thermal mass offers pronounced benefits for thermal comfort and energy savings.

Using an Element Analyzer to estimate the amount of carbon sequestered in the plant material, it was found that the carbon concentration (fraction of overall weight) in orange peels is 44%, which is virtually identical to that of hemp shives and similar to that of constituent organic molecules (46% for pectin and 49% for cellulose). This finding is being used for an ongoing life-cycle assessment of OP and HL biocomposites, with indications that both show potential as promising “circular solutions” for the built environment.

Figure 6: (left) OP biocomposite samples with varying OP particle size, water content, and binder ratio; (right) test cell walls, with respective 10 cm-thick layers of external orange peel (OP) biocomposite insulation and internal rammed earth (RE) mass, before plastering and roof installation.

2.3.2. Pilot demonstration of an edible green wall in Malmö, Sweden

Project title: Seved Edible green wall

Location: Malmö, Sweden (55°35'N 13°00'E)

Year of Design and construction: 2013

Design: Odla i stan/Odlinsnätverket Seved/student från Malmö Högskola using system Gro-Wall

Contractor, installation: Peab (Nordic construction and civil engineering company) together with Peabskolan (a secondary school that trains within the framework of the national high school program building and construction)

Initiator: Föreningen Odlingsnätverket Seved (non-profit organization)

Co-financed: City of Malmo and MKB (*Malmö* Kommunala Bostads), Malmö Planterings- och försköningsförening (Planting and Beautification Association)

Nature-based Solutions Services: green edible wall, recycled material

Case study by: Alisa Korolova

The Seved Edible green wall in Malmo, Sweden was created in 2013 as a pilot project for the demonstration of vertical community gardens (Fig. 7). The main idea was to inspire property owners to use the city space in a new way, as in many areas a lack of space does not allow residents to create community gardens or to grow plants in containers. The wall structure, which has a total area of 50 m^2 and a maximum height of 5 m, accommodates edible plants throughout the whole year – with specific plant types replaced depending on the season. The "summer wall," which includes plants such as strawberries, chard, lettuce, celery, spinach and herbs (oregano, lavender or rosemary), is cultivated from May until November. In November the "summer wall" is replaced by the "winter wall," which is represented mostly by green cabbages and herbs like oregano and thyme. The selection is mainly determined by the visual aesthetics of the plants, with a preference for those that are bushy and compact – while plants that are especially sensitive to wind are generally avoided.

The wall is made up of a modular system called Gro-Wall (https://www.gro-wall.com.au/). The system comprises a grid of compartments that are made from felt cloth bags, supplied by Mardam Agentur. The framework for attachment of the bags to the wall is made by Peab, who set up the wall together with the Peabskolan students. The irrigation is handled by an automated drip irrigation system, which is regulated via computer, together with manual watering by a management team from Odlingsnätverket Seved and the local community.

In 2014, Malmö adopted a comprehensive urban farming program, to get a better overview of the possibilities and with the aim of further promoting the city gardening concept.

Lessons learned:

- The Gro-Wall system is made of 100% recycled plastic, demonstrating the potential of circular solutions.
- The modular system allows diverse design, and can accommodate the use of vertical space for edible plants all year round.
- Cooperation between land/building owners, professionals and students, together with the engagement of an NGO, is a key to successful implementation.
- The project embodies important steps towards social sustainability, by providing support to the local community.

Figure 7: Seved Edible garden (left); and Seved Edible green wall (right). (Photos: Alisa Korolova)

2.3.3. Demonstration of experimental green roof and allied technologies in the "Urban Hydraulic Park"

Project Title: “Integrated and Sustainable management service for water-energy cycle in urban drainage systems” (Scientific Leader: Patrizia Piro)

Location: Rende, Italy (39°22'N 16°13'E)

Years of Design and Construction: 2011 – 2014

Area: The total area of all Experimental Sites located at the Urban Hydraulic Park is more than 700 m^2.

Design: Urban Hydraulics and Hydrology Laboratory – University of Calabria (Scientific Supervisor Prof. Patrizia Piro) with the cooperation of the companies involved in the Project.

Co-financed: Italian National Operative Project (PON) — PON01_02543

Nature-based Solutions Services: Green roof, Permeable Pavement, Stormwater Filter.

Case study by: Patrizia Piro

The "Urban Hydraulic Park" is an experimental demonstration site located at the University of Calabria, Italy, and specifically in the Vermicelli catchment (27.80 ha) where a series of Nature Based Solutions have been implemented to investigate their efficiency in terms of hydraulic, thermal and environmental benefits. The Park includes a green roof with a rainwater harvesting system, a permeable pavement, a stormwater filter, and a traditional sedimentation tank connected to a treatment unit. It is also equipped with a complex monitoring and acquisition system for the collection of climatic, hydrological, hydraulic, and thermo-physical data in real time.

The green roof experimental site shown in Figure 8 (Piro et al. 2019) is parcelled into four hydraulically independent sectors with an area of about 40-50 m^2 each: three vegetated roofs and one conventional roof used as reference for the hydraulic and energetic analysis. While the three green roofs differ in terms of their drainage layers and/or the presence of vegetation, they all generally consist (from top to bottom) of a vegetated layer, a soil substrate, a permeable geotextile, a drainage and storage layer, an anti-root layer, and a waterproof membrane. Two sectors were covered by the same native Mediterranean plants (*Carpobrotus edulis*, *Dianthus gratianopolitanus*, and *Cerastium tomentosum*), while the third one hosts colonized plants. The water supply is guaranteed by reusing the green roof's outflow, which is collected in a storage tank (1.5 m^3) placed at the base of the building and distributed through a drip irrigation system during drought periods.

The permeable pavement experimental site (Figure 9) was built in a portion of an existing car park. It has an area of around 380 m^2, divided into two sections: one of about 150 m^2 with permeable pavement, and the other left impermeable for use as a reference. It has an average slope of 2%, and a total profile depth of 0.98 m. The surface wear layer consists of porous concrete blocks characterized by high permeability (8 cm depth); while the base layer (35 cm depth); sub-base layer (45 cm depth) and bedding layer (5 cm depth) were defined by following the suggestions of the Interlocking Concrete Pavement Institute (ICPI), which recommends certain ASTM stone gradations.

Finally, the stormwater filter experimental site (Figure 10), installed downstream from the permeable pavement, is used to treat stormwater runoff discharged from the adjoining impervious parking lot. It has a surface area of around 125 m^2, an average slope of 2%, and a total profile depth of 0.75 m, and is covered by a soil substrate vegetated with Mediterranean species. A high permeability geotextile is placed between the soil substrate and the filter layer to prevent fine particles from migrating into the underlying layer. The filter layer is composed of highly permeable gravelly material. Finally, an impervious membrane at the bottom of the profile prevents water percolation into deeper horizons.

Lessons learned:

- Each NBS represents a "low impact development" solution, with a specific stratigraphy designed by taking into account the climate condition and the regulations in force.
- From analysis of the monitoring data, all of these solutions improve urban stormwater management in terms of surface runoff mitigation and water quality enhancement.
- From investigation of energetic data, the green roof proves to be suitable for reducing the temperature variation in the building and mitigating the urban heat island effect
- The LCA analysis carried out for the specific green roof and permeable pavement confirms the sustainability of these low-impact infrastructures (Maiolo et al. 2017).

Photo Credits: Urban Hydraulic and Hydrology Laboratory (http://www.giare.eu/) – Scientific Supervisor: Patrizia Piro

Figure 8: The green roof experimental site at University of Calabria.

Figure 9: The permeable pavement experimental site at University of Calabria.

Figure 10: The stormwater filter experimental site at University of Calabria.

2.3.4. Zollhallen Platz in Freiburg, Germany

Project Title: Zollhallen Platz

Location: Freiburg, Germany (48°0’ N/7°50’ E)

Year of Design: 2009-2010

Year of Construction: 2011

Area: 5600m^2

Design Company: Ramboll Studio Dreiseitl

Nature-based Solutions Services: Water-sensitive urban design, biodiverse local planting, reuse of existing material in new design

Case study by: Dimitra Theochari

Zollhallen Plaza is located at the entrance to a historic train station designated for customs that was restored in 2009 (Figs. 11-14). Although the scale of the plaza is small, and it was initially designated to be a simple hardscape area for the new users of this public building, the design team set an ambitious target: to disconnect the plaza from the sewer system, and to create a small-scale urban plaza that would be an example of water-sensitive urban design (WSUD). A series of infiltration points located in the plaza through planters, connected with subsurface gravel trenches and in-built filter medium, are used to reduce the hydraulic overload on the sewer system. The plaza is designed to hold on its surface the volume of water generated by a 20-year, a 50-year and a 100-year rain-event, and to provide flood safety to the city while recharging the ground water table.

In terms of material reuse on site, the rail pieces from the rail yard are reused to structure the inlets of the infiltration with perennials and ornamental grasses, creating an aesthetic appeal of small scape colourful planting. All of the hardscape materials are high-quality demolition materials recycled from the old rail yard, a fact that makes this case study a true example of NBS in circular city principles. In this way, the design evokes the continuity of special historic and cultural features, and the memory of people who worked in the area – contributing further to the social dimension of ecosystem services.

Lessons learned:

- The hardscape of a small city plaza can be used to create a stormwater management system and extreme flooding management system, independent of the city sewer.
- The project demonstrates circular city applications for material and water that falls on site.
- An on-site water circulation system with an underground storage tank is charged with infiltration through permeable paving.

Photo Credits: Dimitra Theochari

Figure 11: Local planting and view to the old train station of Freiburg. The details of the train tracks and the memory of the area is brought back in a system showing applicability of circular city material recycling applications (left), and details of seating designed as being peeled-off the ground to allow for maximizing the space for permeable green surfaces that are entry points to the infiltration system to the underground storage, but also to the groundwater reservoir (right).

Figure 12: Connecting the hardscape to the green zones, extending the ecology and urban nature qualities of the site.

Figure 13: Details of planting and the recycled train tracks from the site.

Figure 14: View of the seating as used by visitors and locals. Area to relax and contemplate urban nature (left); and seating in the green zone and looking out to the city (right). The plaza stormwater system is disconnected from the municipality sewer.

2.4. Critical analysis of NBS in the built environment

2.4.1. Ecosystem services and disservices

Living vegetation that is integrated with or adjacent to buildings – including green roofs, balconies and facades, as well as gardens, parks and isolated trees – are part of a city's green infrastructure. Despite their urbanized surroundings, these green spaces host a wide range of animal species. Whether the vegetation is long-established or newly-planted, many vertebrates and invertebrates find shelter and food in these areas, including in the soil. Thus, the greening of the built environment contributes to biodiversity by decreasing the impacts of habitat fragmentation in urban ecosystems, and by increasing the permeability of the urban matrix (Martin-Queller et al. 2017). This biodiversity also supports a wide range of ecosystem services that contribute to the improvement of human health and wellbeing (Pinho et al. 2017).

Urban greening is invaluable for achieving the three main objectives of integrated water management – enhancing water availability, improving water quality and reducing water-related risks (WWAP, 2018). Understory plant species contribute to regulating water quality by controlling nutrient runoff (Livesley et al. 2016), thus decreasing the resources required to deal with polluted water. Vegetation provides air quality regulation, by preventing pollutants from reaching buildings (Matos et al. 2019), thus decreasing the impacts and cost of air pollution in sensitive areas. Local invertebrates contribute to pollination, which together with birds also provide pest regulation (Mexia et al. 2018). Green spaces also increase the cultural sense of attachment to the place and to nature, with further benefits to wellbeing (Luz et al. 2019).

In addition to providing ecosystem services, however, the establishment and restoration of planted areas in the midst of buildings may increase the exposure of residents to allergenic material, mostly from vegetation pollen. A list of allergenicity of common tree species is available, and should be taken into account when building or restoring urban green spaces (Cariñanos et al. in press). High vegetation density, although a bonus for biodiversity, may increase some people's sense of insecurity, and thus should be evaluated for each case. High moisture, promoted by excessive watering, may cause an increase in local pest populations.

However, balanced urban ecosystems – most notably those in which the use of insecticides is limited – are likely to mitigate this effect by increasing the local populations of insect parasites or predators, such as birds or other insects (Sanchez-Bayo & Wyckhuys 2019). Planting trees near air pollution sources will increase the local deposition of pollutants (Santos et al. 2017), screening them from the urban air to which urban residents are exposed. While this may benefit those located beyond the trees, however, it may also increase pollution loads for those located between the air pollution source and the trees. Although such trade-offs may have no measurable effect on the average air pollution status in the city, careful planning must take them into account in order to provide the highest air quality where it is needed most.

2.4.2. Implementation of NBS for a resourceful circular city: the role of EU policy and international policy drivers

Through its general environmental legislation, the EU has policies in place to promote nature-based solutions in European cities. These policies aim to ensure that urban residents can enjoy clean air and water and avoid excessive exposure to noise, and that cities deal properly with waste, protect nature and biodiversity, and promote green infrastructure. The European Green Capital (http://ec.europa.eu/environment/europeangreencapital/index_en.htm) and European Green Leaf (http://ec.europa.eu/environment/europeangreencapital/europeangreenleaf/index.html) Award programs are tangible initiatives which allow cities to showcase their environmental performance, and policy instruments such as the Circular Economy Action Plan (http://ec.europa.eu/environment/circular-economy/index_en.htm) even address issues such as resource efficiency and raw materials – which can find application in construction, as well as other sectors.

The EU has also elaborated a vision on how to build a sustainable finance strategy (https://ec.europa.eu/info/business-economy-euro/banking-and-finance/sustainable-finance_en) that can cope with the economic challenges of implementing NBS. With an emphasis on funding society's long-term needs, the goal is to strengthen financial stability by incorporating environmental, social and governance (ESG) factors into investment decision-making. Tangible actions include establishing an EU classification system for sustainable activities, creating standards and labels for green financial products, and fostering investment in sustainable projects.

By adopting the Paris Agreement on climate change and the UN 2030 Agenda for Sustainable Development in 2015, governments from Europe and around the world agreed on a more sustainable and resilient path for our planet, providing environmental, social and economic benefits for all. Better alignment of their agendas on sustainable development could unlock the mechanisms needed to achieve a coordinated perspective, utilizing NBS as a cost-effective way of creating a greener, more sustainable and more competitive circular economies.

However, the EU still needs a tighter focus on nature-based solutions that are targeted directly to green building materials, systems and sites. The main legislative instrument dedicated specifically to buildings is the 2010 Energy Performance of Buildings Directive (EPBD), which like the 2012 Energy Efficiency Directive focuses exclusively on operational energy – and as such, does not cover the overall life cycle impacts of buildings that are crucial to any vision of a circular economy. The intent of achieving "circular buildings" is to comprehensively reduce life cycle impacts, and at the same time provide healthy and comfortable spaces for urban dwellers.

This sort of holistic approach to circularity is still lacking in existing certification systems, though minimum requirements for circular design are in fact part of an EU 2017 framework called Level(s), whose development is ongoing.

The lack of integration between NBS and building-related policy is illustrated by an emphasis on design strategies and products which save energy in a building's operation but have high levels of embodied energy and carbon in their production. For example, the shading of windows to prevent overheating is an operationally energy-efficient strategy, but one which is typically implemented using elements such as roller shutters made from materials like aluminium or other metals and plastics which are energy-intensive in their production. Alternatively, systems that use live plants for shading can reduce the building's environmental footprint in a more holistic manner – but they have yet to be mainstreamed in practice or prioritized in policy. In general, the greening of built surfaces – through the use of plant-based building materials, green roofs and walls, and water-sensitive site design – is still not sufficiently promoted.

2.5. Conclusions: advancing the implementation of NBS in the built environment

In light of the preceding discussion, we may ask why there are no specific EU policies, whether in the form of regulations, incentives, or educational tools, that explicitly promote NBS in the built urban environment. One question to be addressed regards the legal obstacles: once appropriate green technologies are available, specific policies need to be formulated in order to provide a regulatory framework that will allow these alternative approaches to find application in the construction sector, which is very strictly regulated (https://www.cen.eu/Pages/default.aspx). Part of this policy formulation involves the definition not just of technical measures, but of long-term criteria and aims that are aligned with the transition to a circular economy.

If the problem is a lack of information and precedents, then the review of case studies presented above may be seen as a step forward in providing such information. Overall, these case studies demonstrate that existing and developing nature-based solutions in the built environment are indeed effective and promising. We would argue that it is the implementation of these existing approaches that is firstly lacking, and this alone would hold great benefits in terms of sustainable and resilient development. In addition, further research is needed into the technical and societal aspects of these solutions to make then more powerful and appropriate for our future cities.

To the extent that a limiting factor is represented by a lack of technical data and adeptness with appropriate tools, there are existing sustainability indicators that can be leveraged. These include Life-Cycle Assessment (LCA), Material Flow Analysis (MFA), and many other metrics that address circular flow of energy, water and materials in a life cycle perspective. Undoubtedly there is still a need for R&D on design tools that are scientifically robust and at the same time accessible to designers and consultants. Among other things, better definitions of minimum performance levels, multiple functions, and valorisation of side effects should be included in decision making systems regarding the implementation of NBS in the built environment.

Further research into building-related NBS thus needs to be prioritized. The indicative case studies presented here suggest that funding for further pilot studies, demonstrations, and experimental monitoring data is crucial. Systematic analysis of the performance of NBS needs to be conducted with reference to conventional technical systems, so that the relative benefits may be quantified. Cost-benefit analysis of NBS against other solutions can only be done in a case-by-case analysis, but an emerging pattern when evaluating the success of NBS is that it must: 1) involve a large number of stakeholders and their interests; and 2) be shown to be a sustainable solution not only ecologically, but economical and socially as well (Nesshover et al. 2017).

We may also draw specific conclusion regarding the three levels of the built environment addressed in this paper: green building materials, systems and sites.

- *Regarding green building materials*: We emphasize that in contrast to the vernacular, modern construction is largely based on manufactured materials that offer reliability and convenience – but that these properties are usually attained through high-temperature, resource-intensive processes that generate considerable waste and atmospheric emissions. Biocomposite materials, which draw on the environmental benefits of nature-based ingredients but also fulfil the required attributes of modern construction thanks to their protective matrix, can make a significant contribution in the transition to a circular economy. A holistic life-cycle analysis can help to identify the sustainability potential and weak-points of such solutions.

- *Regarding green building systems*: A huge variety of building greening systems are already marketed, all promising to mitigate negative impacts of built environments. However, they come with different environmental, economic and social costs, onsite and offsite – "green" does not mandatorily mean "sustainable". The integration of circular economy approaches can improve building greening system's efficiency, sufficiency and consistency. Prior to investing tax money in NBS it will be crucial to prioritize these systems regarding their ecological, economic and social impacts using holistic life-cycle analyses. LCAs can be used to identify both optimization potentials and best practices. In order to conduct them in a reproducible and transparent way, a harmonised set of a-priori weighted assessment criteria has to be employed and clearly documented.
- *Regarding green building sites*: Especially at the scale of semi-public and public open spaces, the effective integration of NBS can meaningfully contribute to resolving larger scale societal challenges locally, by making cities more healthy and inclusive as well as more resource-efficient. In particular, urban food production can support action toward urban resilience and social cohesion. Water-sensitive urban design approaches and a shift from conventional "grey" infrastructure to blue-green infrastructure solutions offer flood safety, resilience and opportunities to close the water cycle on every site. Moreover, green building sites contribute in terms of noise mitigation, biodiversity connectivity, microclimate mitigation and outdoor comfort, while often their benefits are multiple and overlapping, including these and many more ecosystem services. It should be noted that the green building sites are also the designated areas where the offset of the carbon footprint of the development can be placed.

Finally, it is crucial to see green building materials, systems and sites as part of a holistic urban web. When different types of NBS are combined in an integral way – creating a multi-scale network of urban blue-green infrastructure – then the paradigm shift toward circularity will indeed be on its way.

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2.8. Appendix 1: Green roof projects in Greece

Title	Location	Building type	Year of installation	Area (m^2)	Type of funding	Type of NBS	Other technical parameters
Faculty of Philosophy, Library, AUTH	Thessaloniki, Greece	Public use	2011	700	Public	Systems, Materials	Dry tolerant flora
Town Hall of Marousi, Athens	Attica	Public use	2015-2016	415	Public	Systems, Materials	Mediterranean flora
Town Hall of Edessa	Edessa	Public use	2015	700	Public	Systems, Materials	Mediterranean flora
Stavros Niarchos Municipal sport and recreation park of Kallithea	Attica	Public use	2013	23800	Private donation	Systems, Materials, Sites	Endemic, dry tolerant flora
Commercial shop Carrefour	Attica	Public use	2009	700	Private	Systems, Materials	Mediterranean aromatic flora
Residence in Petralona, Athens	Attica	Private use	2008	130	Private	Systems, Materials	Mediterranean flora
Residence in Ekali	Attica	Private use	2011-2012	260	Private	Systems, Materials	Herbaceous plants, shrubbery, vines
Residence in Ekali	Attica	Private use	2009	230	Private	Systems, Materials	Endemic, aromatic flora
Residence in Alimos	Attica	Private use	2013	170	Private	Systems, Materials	Aromatic, flora, shrubbery
Office building in Peania	Attica	Public use	2012	8500	Public	Systems, Materials, Sites	Endemic, dry tolerant flora
Office building in Athens	Attica	Public use	2009	24	Public	Systems	Dry tolerant flora, shrubbery
Office building in Piraeus	Attica	Public use	2009	1000	Public	Systems, Materials, Sites	Gramineae flora
METKA office building in Marousi, Athens	Attica	Public use	2010	700	Public	Systems, Materials, Sites	Mediterranean flora
Metropolitan college in Marousi	Attica	Public use	2016	460	Public	Systems, Materials, Sites	Sedum flora

Research Committee building in AUTH	Thessaloniki	Public use	2011	400	Public	Systems, Materials	Aromatic plants dry tolerant flora
Bank of Greece building	Thessaloniki	Public use	2009	2100	Public	Systems, Materials, Sites	Succulents, dry tolerant flora
Amanzoe hotel complex	Peloponese	Public use	2011-2012	8000	Public	Systems, Materials, Sites	Mediterranean flora, trees
Residence in Petristeri	Attica	Private use	2000	200	Private	Systems, Materials	Endemic shrubbery, aromatic flora
Residence in Psychico	Attica	Private use	2006	130	Private	Systems, Materials	Shrubbery &trees of medium growth
Residence in Nea Erithrea	Attica	Private use	2007	80	Private	Systems	Endemic, dry tolerant flora
Residence in Athens	Attica	Private use	2008	110	Private	Systems	Shrubbery &trees of medium growth
Residence in Athens	Attica	Private use	2008	70	Private	Systems	Shrubbery &trees of medium growth
Residence in Sifnos	Cyclades	Private use	2009	240	Private	Systems, Materials	Endemic flora of sifnos
Office building in Glyfada	Attica	Public use	2010	140	Public	Systems	Endemic shrubbery, aromatic flora
Residence in Nea Smirni	Attica	Private use	2007	45	Private	Systems	Shrubbery of medium growth
Residence in Filothei	Attica	Private use	2007	110	Private	Systems, Materials	Shrubbery of medium growth
Residence complex in Politia	Attica	Private use	2008	350	Private	Systems, Materials	Aromatic flora
Hotel complex in Paros	Cyclades	Public use	2009	130	Public	Systems, Materials	Aromatic flora
Ministry of Finance building	Attica	Public use	2008	650	Public	Systems, Materials	Succulents, dry tolerant flora
Hotel complex in Zante	Ionian islands	Public use	2009	1500	Public	Systems, Materials, Sites	Endemic aromatic flora, shrubbery

2.9. Appendix 2: Case studies of urban green sites from Bratislava, Slovakia (48°N 17°E).

Project title	**Size**	**Description**	
Senior Home Archa*	ca. 1400 m^2	Extensive green roofs reduce solar effects and runoff. Source: www.bratislavazelnajsa.sk. Photos: www.bratislavazelnajsa.sk.	  
Pocket park Svoradová*	ca. 1000 m^2	Natural character of formerly used site preserved, offering environmental and ecological functions in urban area and maximizing rainwater use. Two round concrete tanks connected to a pumping device are believed to be WW2 water tanks built for civil protection purposes. Source: www.bratislavazelnajsa.sk. Photos: Erika Igondová	  
Frontiersmen square*	ca. 8650 m^2	Natural elements increase aesthetic potential, improve usability and create climatic comfort in a busy park. Existing greenery preserved and green space revitalised, reducing paved surface. Automatic irrigation system implemented, and rainwater drained from non-permeable surfaces into grassy areas. Source: www.bratislavazelnajsa.sk. Photos: Erika Igondová	  

JAMA Sportspark*	ca. 17000 m^2	Spectacular multi-use park improves quality of life even on city level. Rainwater drained into new artificial lake, fulfilling aesthetic, climatic and water-catchment functions and providing a source of park irrigation. Sources: www.bratislavazelnajsa.sk; www.archinfo.sk. Photos: Erika Igondová	  
Central Shopping Center – rooftop garden	ca. 6000 m^2	Multifunctional complex with spacious green roof park. Greened terraces use membrane with inlay of non-woven glass to resist root penetration; non-accessible roofs protected by membrane covered with gravel. Intensive green roof offers sustainable rainwater management and climate change mitigation measure. Source: www.stresnesubstraty.sk. Photos: Erika Igondová	  
Water-managemen t community garden	ca. 2500 m^2	On premises of Water Management Museum close to Danube River. Elevated beds for growing vegetables, fruits and a herb garden. Old but functional greenhouse and couple of beehives. Community garden based on permaculture gardening principles: “the conscious design and maintenance of agriculturally productive ecosystems which have the diversity, stability, and resilience of natural ecosystems.” Source: www.spectator.sme.sk. Photos: Erika Igondová	  

* The first four case studies are part of the project "Bratislava is preparing for climate change – the pilot application of measures in sustainable rainwater management in an urbanized environment" (www.bratislavazelnajsa.sk). This project was awarded a grant of the financial mechanism of the European Economic Area, Norway grants and the state budget of the Slovak Republic for the period 2014 -2017. The project partners implemented a total of 32 individual adaptation measures in the city on 12 sites. Among these measures were 2 sustainable drainage systems, 1 green wall, 3 green roofs, 3 sites at which impermeable surfaces were replaced with permeable material, 3 sites at which public greening including trees was revitalized, 3 sites at which public greening including trees were newly planted, 1 site with revitalisation of natural area threatened by erosion, and 6 newly created components of green infrastructure. Project consortium: Bratislava City (project beneficiary, leader) + project partners: city boroughs Bratislava-Petržalka and Bratislava-Nové Mesto, Bratislava Urban Forests Ent., Bratislava Water Company, Comenius University in Bratislava, Bratislava Regional Association for Nature Conservation and Sustainable Development (BROZ), General Investor of Bratislava, COWI – Norwegian environmental consultancy company.

3. WG2 review paper

Describing Nature Based Solutions for Urban Water Management towards Resourceful Circular Cities: State of the Art and Case studies

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Abstract

Nature-based Solutions (NBS) are engineering solutions to protect, sustainably manage, and restore natural or modified ecosystems, in order to address socio-environmental challenges effectively, while preserving and improving nearby human well-being. The challenges include climate change, water security, water pollution, food security, human health, and disaster risk management. In regard to the expected impacts of climate change, the sustainable management of water resources, flow water management, water use and wastewater treatment in urban areas is an essential factor for the preservation of livelihood in cities. This state of the art paper aims to discuss the relevant NBS for urban water management regarding resourceful circular cities. For this purpose, NBS from relevant literature and representative case studies from European member countries are presented and analysed. The method used in the study is based on a detailed tracking of the keywords in the literature using the Google Scholar, ResearchGate, Academia.edu, ScienceDirect and Scopus. Based on this review three main challenges were identified: i) flood and drought protection; ii) the water-food-energy nexus; and iii) water purification. The paper shows that NBS provide additional benefits, such as improving water quality, increasing biodiversity, obtaining social co-benefits, improving urban microclimate, and the reduction of energy consumption by improving indoor climate. The paper concludes that NBS should be given a higher priority and be preferred over conventional water infrastructure.

Keywords

Nature-based solutions; urban water; climate change resilience; stormwater; wastewater treatment.

3.1. Introduction

According to one of the latest Intergovernmental Panel on Climate Change (IPCC) reports, global climate change will cause irreversible harm to humans, the built environment and the biosphere (IPCC, 2018). In particular, the depletion and degradation of pristine water resources is expected to cause unprecedented harm to humans and the environment. In addition, the rapid increase of urban areas, resulting in a higher demand for water resources as well as disruption of the natural water cycle, accentuate the importance of sustainable and resilience-based water management. Hence, it is essential for urban water management to be an integral part of urban planning. Moreover, land use decisions affect water supply and wastewater system designs and operation, as well as measures needed for managing stormwater runoff. Furthermore urban infrastructure system requires energy, which in turn, typically requires water (Loucks and Van Beek, 2017). Consequently, water is one of the key elements of the United Nations Sustainable Development Goals (SDGs), alone or interlinked with the different aspects. For instance, several of the 17 objectives are strongly connected to urban farming and call for an economical utilisation of assets, environment rebuilding, biodiversity, carbon sequestration, feasible catchment management and soil management (Keesstra et al., 2016).

Urban water refers to all water that is present in urban environments which includes natural surface water, groundwater, drinking water, sewage, stormwater, flood overflow water and recycled water (a third pipe, stormwater harvesting, sewer mining, managed aquifer recharge, etc.). Furthermore, a wide range of techniques can solve urban water related problems, for example, improving water use efficiency and demand reduction techniques, water sensitive urban design techniques, living streams, environmental water and protection of natural wetlands, waterways and estuaries in urban landscapes (water.gov.au, 2017). Larsen and Gujer (1997) defined Urban Water Management (UWM) as a combination of water supply, urban drainage, wastewater treatment, and water-related sludge handling. Accordingly, UWM includes the plan, design and operation of infrastructure to secure drinking water and sanitation, the control of infiltration and stormwater runoff, recreational parks and the maintenance of urban ecosystems.

Sustainable urban development includes a holistic management approach consisting of the water-energy-food nexus, land use, and the diversification of water sources for reliable supplies (Kalantari et al., 2018). Further, Integrated Urban Water Management (IUWM) provides a framework and objective for planning, designing, and managing urban water systems. Moreover, IUWM is a flexible process that responds to change and enables stakeholders to participate in, and predict the impacts of development decisions. Consequently, adequate IUWM includes the environmental, economic, social, technical, and political aspects of UWM. It enables better land use planning and the management of its impacts on freshwater supplies, treatment and distribution; wastewater collection, treatment, reuse, and disposal; stormwater collection, use and disposal; and solid waste collection, recycling, and disposal systems. Accordingly, it makes urban development part of integrated basin management, which is oriented toward a more economically, socially and environmentally sustainable mixed urban-rural landscape (Loucks and Van Beek, 2017; Kalantari et al., 2018; Arabameri et al., 2019).

As a result of increasing urban areas, the interaction of many factors such as demographic, economic, political, environmental, cultural and social factors creates challenges related to the use and management of water resources. Several of these issues can be addressed with Nature Based Solutions (NBS). NBS aim to protect, sustainably manage, and restore natural or modified ecosystems. NBS address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits (IUCN, 2018). NBS also have the potential to underpin a sustainable water management strategy (FAO, 2018).

This study is conducted under the European Cooperation in Science and Technology (Cost), which funds the research Action “CA17133 - Implementing nature-based solutions for creating a resourceful circular city”. This study aims to offer a brief state of the art review on NBS for urban water management, together with a description of some relevant projects running within the action. In this COST Action, the definition of a common language and understanding across disciplines are seen as a crucial success factor, while Circular Economy (CE) concepts are seen as key approach and NBS or Green Infrastructure (GI) solutions are seen as core elements of the toolbox (Langergraber et al., 2019). Our working group has focused on the implementation of a safe and functional water cycle within the urban biosphere, where wastewater needs to be streamlined as a source of nutrients, hazardous pollutants need to be controlled (e.g. heavy metals or emerging organic contaminants), heavy metals being phytomined, the treated water looped back for irrigation, and recreational purposes should be considered side by side with sanitation, water supply or stormwater management. Furthermore, we critically appraise the established centralized water flow, defining available resources within the water flow and risk assessment on urban water, NBS for stormwater management and wastewater treatment.

The main research question addressed in this paper is “How can NBS be integrated with the sustainable urban water management?” To answer this question we followed two parallel approaches: i) a traditional literature review targeting a set of different subtopics, coupled with ii) an overview of case studies from projects running within the framework of the COST Action. By combining both, we wish to provide not only the most complete overview of the current existing knowledge but also to discuss and challenge the current existing frameworks for NBS implementation. Therefore, the aim of this state of the art paper, is to define the challenges, present benefits and future trends, provide an overview of the usage of NBS for urban water management and to offer implementation recommendations for urban water utilisation towards circular cities.

The paper is organized as follows: Section 2 presents both the framework for literature review and the selection criteria of relevant case studies; Section 3 describes the state-of-the art through existing NBS tools for sustainable water management, subdivided in 3.1 stormwater management, 3.2 flood protection and risk management, 3.3 implementation of blue-green infrastructures, 3.4 urban water in the field of food, water, and energy ecosystem, and 3.5 urban water pollution control: constructed wetlands. Section 4 describes some case studies linking them with the existing literature. Finally, Section 5 offers a brief discussion and some concluding remarks are provided to point the way forward an increased implementation of NBS for the urban water management.

3.2. Methodology

Because of the broad scope of the topic, different levels of implementation of NBS and availability of international peer reviewed literature for certain subtopics, we propose a combined approach where both existing literature and case studies were reviewed using different criteria. This section is divided into two subsections. In the first subsection, we present the details of the literature survey to collect data of relevant international peer-reviewed journals, while in the second we describe the criteria for selecting relevant case studies important for the current review.

3.2.1. Literature review approach

The literature survey was performed independently by different sub-groups of authors involved in this work. Therefore, the details of the literature search are described in the next paragraphs per each sub-section .

For the stormwater management section literature was searched in Google Scholar, ResearchGate, Academia.edu, ScienceDirect and Scopus by using the keywords "stormwater management" AND "nature based solutions", "stormwater management" AND "historical development", "climate change" AND "resilience". A total of 40 manuscripts (i.e., 10 Google Scholar, 2 ResearchGate, 2 Academia.edu, 15 ScienceDirect, 4 Scopus, 7 other publications were retrieved by cross-checking references from the initial retrievals from the databases) were retrieved and revised. After the first screening of the abstracts, 19 papers were disregarded and 11 were read and presently discussed in this paper.

For flood protection and risk management section literature was searched in Google Scholar, ResearchGate, ScienceDirect and Scopus by using the keywords "flood" "risk management" AND "nature based solutions". A total of 34 manuscripts (i.e., 12 Google Scholar, 3 ResearchGate, 10 ScienceDirect, 3 Scopus, 6 other publications were retrieved by cross-checking references from the initial retrievals from the databases) were retrieved and revised. After the first screening of the abstracts, 23 papers were disregarded and 11 were read and presently discussed in this paper.

For implementation of blue-green infrastructures section for flood protection and risk management section, literature was searched in Google Scholar, ResearchGate, ScienceDirect and Scopus by using the keywords "flood", "risk management", AND "nature based solutions". A total of 45 manuscripts (i.e., 10 Google Scholar, 12 ResearchGate, 8 ScienceDirect, 10 Scopus, 5 other publications were retrieved by cross-checking references from the initial retrievals from the databases) were retrieved and revised. After the first screening of the abstracts, 26 papers were disregarded and 19 were read and presently discussed in this paper.

For the urban water pollution control section, a total of 60 manuscripts (i.e., 20 Google Scholar, 10 ResearchGate, 15 ScienceDirect, 10 Scopus, 5 other publications) were retrieved by Google Scholar, ResearchGate, ScienceDirect and Scopus by using the keywords "nature based solutions" AND "urban water pollution control". Among them, 10 papers were disregarded and 50 were read and discussed.

For the water, energy food nexus section, literature was searched in Google Scholar, ResearchGate, ScienceDirect and Scopus by using the keywords "nature based solutions" "water" AND "energy" AND "food nexus". A total of 36 manuscripts (i.e., 4 Google Scholar, 1 ResearchGate, 12 ScienceDirect, 2 Scopus, 17 other publications were retrieved by cross-checking references from the initial retrievals from the databases) were retrieved and revised. After the first screening of the abstracts, 13 papers were disregarded and 23 were read and presently discussed in this paper. This section also generated two supplementary tables: SM-Table 1 overviews the existing NBS and their link with the water-food-energy nexus and SM-Table 2 compares Groundwater-Based Natural Infrastructure solutions with grey infrastructure.

3.2.2. Case studies selection criteria

International projects in which the CA1733 action members are directly involved dealing with NBS and sustainable water management were selected as case studies for this article. The data related to these case studies was obtained from the researchers involved in both the projects and COST action. Figure 1 shows the geographical location of the case studies further detailed in section 4.

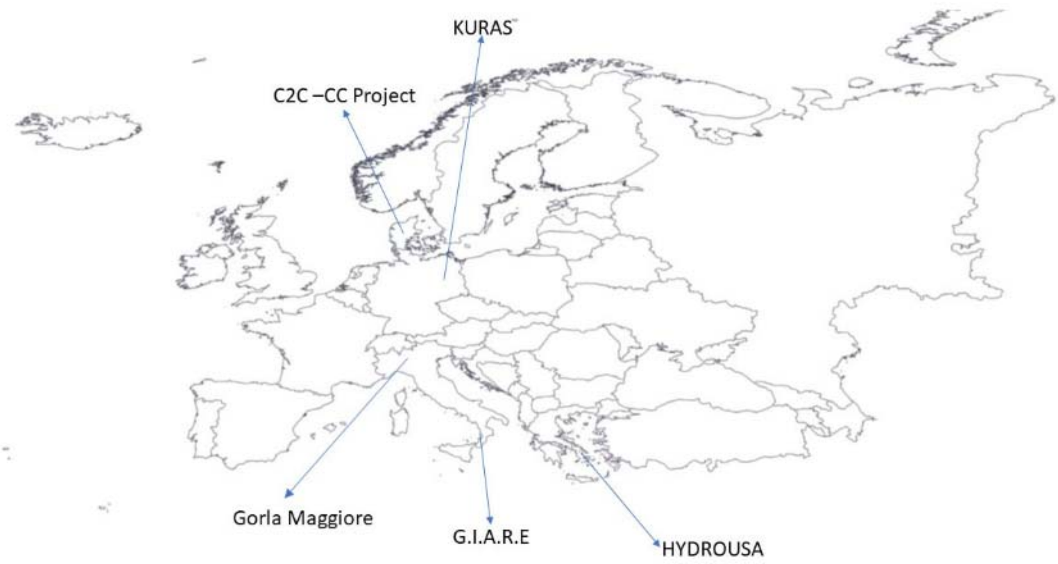

Figure 1. Location of reviewed case studies within the COST Action.

3.3. State of the art of the existing NBS tools for sustainable water management

In times of anthropogenic climate change, urban regions around the world face natural disasters such as heat islands, droughts, and floods as well as urban pressures, for instance, air and water pollution along with resource management inefficiency. Consequently, the sustainable development of urban areas resulted in decision-makers being caught in challenging situations, while simultaneously having to solve the problem of the excess of one resource and the lack of others. Therefore, based on individual cases, it seems rational to consider the possibility of implementing the concept of the circular economy in addition to connecting two problems – instead of defining them and seeing one aspect as the solution for other elements of a healthy urban socio-environmental system.

In this section, we group the sustainable water management under five categories as (i) stormwater management (ii) flood protection and risk management (iii) implementation of blue-green infrastructures (iv) urban water in the field of food, water, and energy ecosystem (v) urban water pollution control: constructed wetlands.

3.3.1. Stormwater management

In recent years, stormwater management has become an increasingly multidimensional and multidisciplinary issue. Moreover, stormwater presents very distinct qualitative and quantitative characteristics from domestic sewage. It is recognised as the most important source of heavy metals, whereas wastewater constitutes the main source of organic and nitrogenous pollution (Barbosa et al., 2012; Brown et al., 2013; Bavor et al., 2001; Eriksson et al., 2007).

In many countries, separate sewer systems are predominant, and most rainwater networks discharge rainwater directly to receiving waters, without any purification, which is a serious threat to the quality of such water. This is particularly dangerous for small watercourses flowing through cities for which rapid discharge from rainwater drainage systems exceeds the hydraulic capacities, and the introduced pollution load is a serious threat. Further, until the 1990s, it was believed that the best solution to the rainwater problem in cities should be drainage, i.e. efficiently collecting and discharging stormwater to receiving waters (Figure 2).

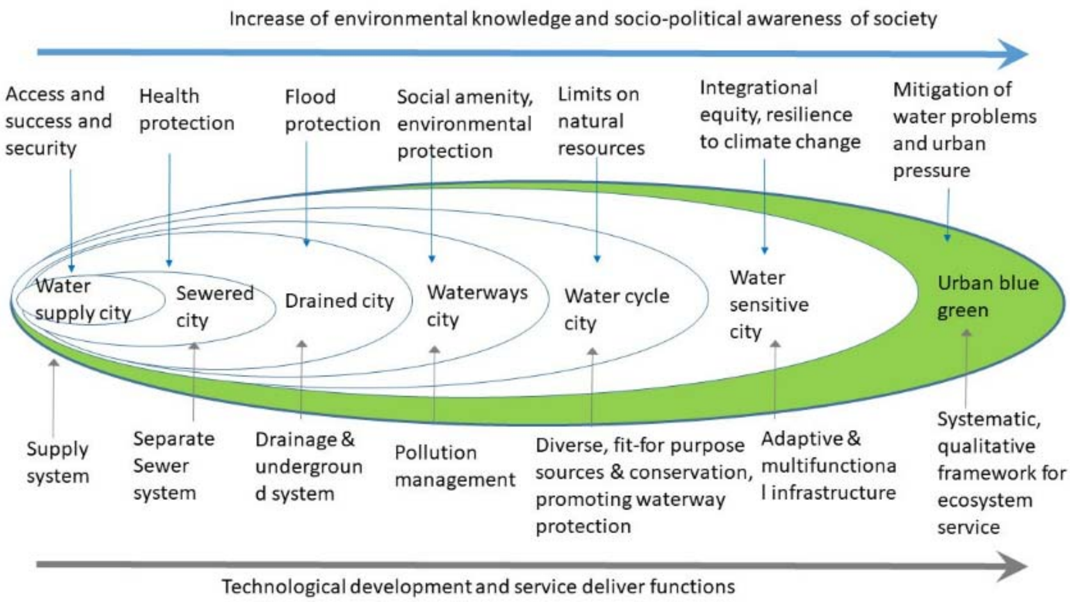

Figure 2. Historical development of water supply and management (modified from Brown et al., 2009 and Blue Green Solution, 2017).

However, progressing urbanisation is inevitably connected to replacing the natural land cover with impermeable surfaces, which leads to increased surface runoff. Additionally, climate change is leading to more volatile rainfall patterns with an increasing number of extreme events, thereby causing frequent overloading of the drainage systems. As a result, floods are occurring, especially in central city districts with a high level of impervious surfaces. Such events, referred to as pluvial flash floods, are followed by long dry spells. For example, over the last 18 years in Gdańsk, Poland, more than four rainfall events with a 100-year return period (i.e. over 100 mm/day) have occurred. On 14/15 July 2016, 160 mm of rain fell within 14 hours, exceeding the total rainfall of two months. On the other hand, as mentioned above, long periods without precipitation are also causing functional problems for cities. Thus, the lack of stored rainwater increases the need for watering urban green areas with irrigation systems. Such approaches require both natural resources and financial support, thereby leading to their unsustainability (Wojciechowska et al., 2017).

Despite the risks that water can pose in urban spaces, it is an integral part of the city and a vital resource for the residents. From the human health perspective, it is necessary to integrate water in the urban layout. Therefore, a modern approach to the urban planning of the so-called Water Sensitive Urban Design assumes the use of the most natural technological solutions, the so-called eco-engineering. We count green roofs, bioretention systems, "rainforests" and hydrophyte systems that combine the function of purification and retention and provide many ecosystem services (ES), including biodiversity and returning rainwater to the local water cycle by evapotranspiration. The natural ground cover would only have 10% runoff with 40% via evapotranspiration and 50% through infiltration while the impervious cover would have 55% runoff with 30% evapotranspiration and 15% infiltration (US EPA, 2003).

As presented above, existing water management systems are not sufficient in many cases, and a need to solve the problem of quantity and quality of water exists in order to implement the concept of an urban circular economy. The synergy of constantly growing urban areas with impervious surfaces and pollution associated with human activities, and climate change with an increasing number of meteorological extremes, requires a new approach for cities to become more resilient to socio-environmental pressures (Figure 3).

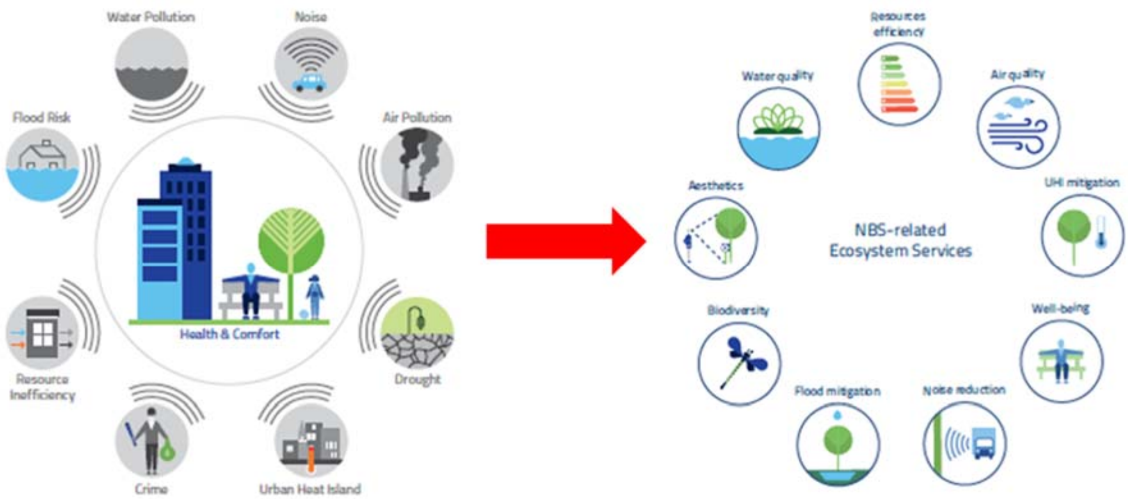

Figure 3. Identified water problems and urban pressures (a) and mitigation options by the application of nature based solutions (Blue Green Solution, 2017).

Therefore, based on the identified challenges, there is an urgent need to support the implementation of NBS in cities in order to contribute to climate change adaptation by reducing their vulnerability to environmental threats. NBS allow to mimic pre-development hydrologic regime and detain runoff close to its source following a principle of low-impact development (Coffmann, 1999; Bavor et al., 2001; Hoyer et al., 2011; Wong & Brown, 2019) and use plants to later return the water to the local water cycle through evapotranspiration, thus supporting the plants in dry periods. Therefore, NBS become an essential feature of urban resilience managing stormwater, contributing to urban cooling through evapotranspiration and alleviating urban heat island effects while supporting urban green with local water resources.

3.3.2. Flood protection and risk management

Ecosystems, depending on their management, can either contribute to the problem or provide effective NBS for flood risk reduction or climate change mitigation and adaptation (Cohen-Shacham et al., 2016). At the same time, the implementation of NBS depends on the state and capacity of ecosystems to provide particular regulating services (flood, erosion, climate). Their spatial dimensions provide a basis for land use management and urban planning decisions in accordance with an ecosystem-based approach for flood risk management and other aspects of urban environmental management (Szopińska et al., 2019). On the other hand, there are other, potentially very cost-effective ways of achieving flood protection by tapping into nature's own capacity to absorb excess waters (EC, 2016b). Consequently, NBS implementation aims of preventing natural disasters to make urban areas safe and resilient, which can be achieved in combination with technological and engineering solutions if necessary.

Planning infrastructures to manage flood risk is related to connectivity (Parson et al., 2015), circularity (Kirchherr et al., 2017; Keestra et al., 2018; Comino et al., 2018) and finding a balance between natural and urban elements (Gaines, 2016). Moreover, in a fast developing city, the loss of circularity is often associated with the altered hydrological cycle, implying that water is not a natural, valuable resource, but rather a threat to the urban environment, when it flows at rates different from those of natural paths, from/toward locations that are functional to the development of human activity rather than to the environmental dynamics, through man-managed (often fast) connections, with quality standards far from those provided by natural water bodies (EPA, 2005).

Consequently, the loss of circularity in the altered natural water cycle is derived from the reduction of soil infiltration capacity and the resulting in fast surface runoff. The fact that the natural water cycle is replaced by the urban water cycle threatens soil, channelised urban drainage systems, receiving water bodies and downstream cities. Furthermore, the wash-off of pollutants from anthropogenic catchments poses a threat to the receiving water bodies and their biomes. The loss of infiltration and uncontrolled leakage from sewage threaten groundwater and connected surface water bodies. Subsequently, the resources, politics, and awareness affect the socio-environmental dynamics and determine whether the socio-hydrological system will undergo irreversible decline or be self-sustainable (Ursino, 2019).

NBS, in this context, is meant to partially recover the pre-development water fluxes and water quality, thus reducing the flood risk (WWAP, 2018). Therefore, the use of NBS in this context is strongly related to the well-known concept of sustainable urban drainage, known in literature with different keywords, such as Sustainable Drainage Systems (SuDS), Water Sensitive Urban Design (WSUD), or Low Impact Development (LID), as reviewed by Fletcher et al. (2015). All these concepts aim to restore the water cycle within an urban catchment, from post-development back to the pre-development state (Fletcher et al., 2013). Thus, based on site-specific characteristics and the aim of implementation (to recover original functionality of the urban catchment or address specific issues linked to water management and risk control), NBS alone may not be able to re-establish complete circularity of the natural water cycle but rather provide multiple services to the community (e.g. mitigate flood and drought risk, affect local climate conditions, increase amenity and biodiversity). Further, based on the scale at which NBS are integrated into the so-called Green-Infrastructure (GI), different benefits can arise (Golden and Hoghooghi, 2018). For instance, Zhang et al. (2019) investigated how NBS across facility, catchment, and continental scales differently impact the hydrological, water quality and bioecological benefits.

3.3.3. Implementation of blue-green infrastructures

One of the most common ways to implement NBS is by the so-called blue-green infrastructure. Blue-green infrastructures are key elements in the holistic planning of (future) urban regions (Winker et al., 2019). Accordingly, blue-green infrastructures bring strategically planned networks of (artificial) natural spaces in cities (Bundesamt für Naturschutz, 2017). Therefore, using NBS, it seeks to minimise the effects of climate change on urban areas and create various ecosystem services with benefits for the society, environment, and economy. NBS can help create natural circumstances in urban areas for "alleviating urban pressures and achieve resilience to climate change" (Maksimovic et al., 2017).

Blue-green infrastructures establish multifunctional structures as diverse green spaces in combination with elements of WSUD (Winker et al., 2019) to strengthen urban sustainable development. Accordingly, "green" infrastructural elements take essential roles in creating a healthy microclimate in cities. For instance, trees reduce flood risks and the effect of urban heat islands and expand shading whilst pocket parks (and streams) aesthetically attract citizens and provide space relieving mental aspects of urban pressure (Maksimovic et al., 2017). "Greening" transforms cities by unsealing surfaces and is applied on building structure to lower the building's energy level by natural cooling, which saves costs and works in aesthetical ways. Further, green rooftops have a multifunctional use within blue-green infrastructures from urban gardening to collecting spaces for rainwater. As precipitation is a scarce resource and floods and droughts will accumulate due to climate change, cities can adapt WSUD strategies which focus on managing all water streams within the city. In addition, water supply from rainwater, stormwater and treated wastewater from a sustainable blue infrastructure for cities and can relieve or replace grey infrastructure (Depietri und McPhearson, 2017). For example, natural or close to natural ways of flood risk prevention such as sponge cities are more sustainable than flood walls. In combination, blue-green infrastructures provide health benefits for society and relieve the pressure on the environment and urban space. Furthermore, blue-green infrastructures are more cost-effective than the current predominant urban infrastructures. As such a long-term sustainability approach can be pursued with regard to the design of the cities of the future.

The urban blue-green infrastructures provide various valuable regulating ecosystem services in respect to global climate regulation by reduction of greenhouse gas concentrations through carbon storage and sequestration (Kazak et al., 2016), water flow maintenance and flood protection (Szewrański et al., 2018), micro and regional climate regulation (Ziemiańska and Kalbarczyk, 2018; Kołecka et al., 2018) and improvement of air and water quality (Lakatos et al., 2012; Dąbrowska et al., 2017; Bawiec, 2018). Consequently, creating well designed built environments rich in ecosystem services provide various options for mitigation and adaptation of urban areas for the impact of climate change. Most of the adaptation measures in cities depend mainly on particular urban planning solutions and public regulations. Therefore, based on the technological solutions, local authorities can improve urban development processes by decision support systems, which effectively suggest suitable solutions in the case of many domains of environmental management (Kazak and van Hoof, 2018). Identification and consideration of the dependency of the local population on the particular ecosystem services in the living areas make the valuation of the ecosystem services an important factor in sustainable landscape planning and territorial integration policymaking (Borisova, 2013; Świąder et al., 2018).

As mentioned above, the implementation of blue-green infrastructures does not only solve the problem of water management in cities, but it supplies much more influential ecosystem services on increasing urban resilience to socio-environmental challenges. These ecosystem services can be assessed and mapped for better understanding of the environmental carrying capacity in the land management system to cope with flood hazard at all levels – region, basin, and settlement (Boyanova et al., 2014; Larondelle et al., 2014; Świąder, 2018). In some cases, the ecological boundaries, in terms of the area provided ecosystem services to the cities, exceed their administrative boundaries up to 1000 times (Folke et al., 1997). At the same time, cities rely heavily on the capacity of the ecosystems in the urban environment provided by the green and blue areas. Thus, the interaction between biophysical and geophysical processes determines the potential capacity of natural capital to provide regulating ecosystem services. The water flow can be influenced by several natural processes and functions of the ecosystems, which contribute to the absorption of water and therefore reduce surface runoff or vice versa. The main factors of the capacity for water retention are the vegetation cover, the soil structure and texture, the presence of bare land or water bodies, the slopes and the land cover in the territory. In the study by Nikolova and Nedkov (2018), the flood regulation supply capacity was assessed by an Index of Capacity for Water Retention of urban ecosystems (defined by Zhiyanski et al., 2017). The assessment of flood regulation services is carried out in four main steps according to the methodological framework for ecosystem services assessment developed by Burkhard et al. (2012):

1. Identification of the urban ecosystems with potential to provide flood regulation;
2. Selection of indicators for ecosystem services assessment;
3. Quantification of the ecosystem services indicators;
4. Assessment and mapping of flood regulating urban ecosystem services.

The results of such assessment show that the water retention capacity of residential, industrial and public areas is lower, while urban green areas have higher potential. Thus, detailed assessment gives decision-makers the exact information about the impact of future actions on biocapacity and the ecological footprint of human activity.

3.3.4. Urban water in the field of food, water, and energy ecosystem

Liquette et al. (2016) as well as Leigh and Leed (2019) indicated that the future of urban water systems is shifting towards resource oriented, integrated, sustainable, distributed and nature-based solutions. Accordingly, wastewater treatment will be replaced by the production of goods. Further, one optimised system will allow reaching multiple targets, instead of having a separate infrastructure for every purpose. This should give treated wastewater access to everybody. Multiple targets besides water treatment can be the production of fertilisers, provision of urban green, enhancing biodiversity and cooling, to name just one possible set. These targets must be defined during the concept phase in a case by case approach and their fulfilment must be measurable. According to present knowledge, this is the way forward to eliminate present untreated wastewater releases, a target set in SDG 6 : clean water and sanitation (UN, 2015).

NBS can help face these challenges by providing the means for cities to successfully achieve long-term sustainability in the use of resources (e.g., energy, water, land) and increase urban resilience to climate change (Maes and Jacobs, 2015). Nevertheless, water-energy-food nexus relationships are complex and poorly understood, especially in urban environments, thus leading to significant potential risks. However, there are benefits if the society is able to manage them adequately (Bennett et al., 2016). Further, Bennett et al. (2016) address the water-energy-food nexus and natural infrastructure investment on the entire watershed scale, taking large scale infrastructure investment programs into account, thus going beyond the city boundaries. Consequently, the implementation of NBS in urban areas can benefit from the water-energy-food nexus at local scales to efficiently manage natural resources for the optimal ecosystem services delivery. Nevertheless, to the best of our knowledge, there are no literature reviews focused on the water-energy-food nexus in urban areas and how multifunctional NBS may help manage this nexus to improve the usage efficiency of these resources, thus helping to achieve long-term sustainability of cities. Some recent studies such as Hansen et al. (2015), Lafortezza et al. (2018), Krauze and Wagner (2019) and Keesstra et al. (2018) describe NBS with multifunctional targets and affect the water-energy-food nexus in urban areas. At the European scale, besides the main reports from the EC (2013, 2015), recent studies have analyzed NBS applications in urban environments: Faivre et al. (2017) focus on NBS to address social, economic and environmental challenges in EU areas; Kabisch et al. (2016) review NBS for climate change adaptation in urban areas; Nikolaidis et al. (2017) study new approaches to improve regulatory instruments and demonstrate the long-term value of NBS; Raymond et al. (2017a) develop a framework for assessing and implementing the co-benefits of NBS in urban areas; Russo et al. (2017) review NBS based on edible green infrastructure for better management of the water-energy-food nexus; and the reports from the Naturvation project (Bockarjova and Botzen, 2017; da Rocha et al., 2017; Hanson et al., 2017), which review the different dimensions of NBS implemented in urban areas, including those related to a more efficient use of natural resources and the nexuses between water, energy, and food in NBS.

Most frequently, NBS are designed for: 1) urban water regeneration; 2) watershed management; 3) ecosystem restoration; 4) increasing the sustainable use of matter; 5) generation of renewable energy; and 6) increasing carbon sequestration. Likewise, European authorities (EC, 2013, 2015) have highlighted the multifunctional benefits of NBS to improve resource efficiency in urban areas. Among these solutions, we find: 1) urban agriculture for local food production; 2) water regeneration; 3) green roofs for climate adaptation; and 4) higher energy and water efficient use; 5) regeneration of abandoned land by afforestation; 6) food production; 7) rain gardens for storm-water regulation; 8) and the use of permeable surfaces and vegetation for run-off control. In Tables SM 1 and 2 given as the supplementary material, we present the examples of relevant NBS related to the water-energy-nexus. Finally, one of the main challenges in the topic is the assessment of the performance and impacts of NBS in addressing the objectives of higher resource efficiency and resilience in urban areas. The assessment schemes have been developed to measure performance and impacts through different indicators: Mapping and Assessment of Ecosystems and their Services (MAES) (Maes et al., 2016), Knowledge and Learning Mechanism on Biodiversity and Ecosystem Services (EKLIPSE) (Raymond et al., 2017b) and the Smart City Performance Measurement Framework (CITYkeys) (Bosch et al., 2017). In addition to the examples of relevant NBS related to the food-energy-nexus, the application of groundwater based natural infrastructure solutions and comparison with the grey infrastructure also exist. Table SM-2 presented as supplementary material of this review explains the function, goal, and solution, which are the outcomes of the comparison.

3.3.5. Urban water pollution control: constructed wetlands

Urban water pollution control nowadays is predominantly carried out as an "end of the pipe" solution with highly intensified wastewater treatment systems in order to protect downstream freshwaters from contamination and eutrophication (Finger et al., 2013). Yet, in addition to the benefits related to management of stormwater, flood protection, and efficient use of resources in a water-energy-food nexus discussed in the previous sections, NBS offers an untapped potential for urban water pollution control. The treatment potential of NBS depends, among other factors, on the type of NBS used (infiltration basin, constructed wetland, raingarden, etc.), quantity and quality of water to be treated, and local conditions (climate, precipitation patterns, etc.).

In the concepts of green infrastructure, low impact development and sustainable drainage systems, water pollution control are provided by the so-called planted/unplanted biofiltration systems. According to the definition of Fonder and Headley (2013), planted (surface) systems are a type of constructed wetlands (CWs). Among the various types of the NBS, CWs are the most common and accepted NBS for pollution control nowadays, and they can be used in cities, especially for Masi et al. (2018):

- rainwater treatment;
- combined sewer overflow treatment;
- polishing of the outflow from existing wastewater treatment plants, including for the treatment of contaminants of emerging concern (CEC);

- greywater treatment.

In respect to water quantity and quality, stormwater presents different qualitative and quantitative characteristics compared to domestic sewage. It is recognised as the most important source of heavy metals, whereas wastewater constitutes the main source of organic and nitrogenous pollution (Barbosa et al., 2012). On the other and, the quality of stormwater can vary greatly in time and between locations, especially in the urban areas where over 650 substances were identified in stormwater (Eriksson et al., 2007). Table 1 displays the classification of five main groups of pollutants that can be encountered in stormwater.

Table 1. List of main stormwater pollutants types (Adopted from Eriksson et al., 2007).

Pollutant types	**Indicator parameters**
Basic parameters	Organic matter (BOD_5, COD), suspended solids, nitrogen, phosphorus, pH
Heavy metals	Zinc, cadmium, chromium (VI), nickel, lead, platinum
Polycyclic aromatic hydrocarbons	Benzopyrene, naphthalene, pyrene
Herbicides	Terbuthylazine, pendimethalin, phenmedipham, glyphosate
Organic compounds	Nonylphenol ethoxylates and degradation products, e.g. nonyl phenol, pentachlorophenol, di-2-ethylhexyl phthalate, 2,4,4'-trichlorobiphenyl (polychlorinated biphenyl 28), methyl-tert-butyl ether
Bacterial indicators	Fecal coliforms (*E. coli*), pathogens (*Pseudomonas aeruginosa*)

Typically, NBS are employed to reduce the levels of traditional pollutants such as total suspended solids (TSS), organic matter, nutrients and also heavy metals. TSS belongs to the group of basic pollutants but at the same time are classified as being the most dangerous due to their impact, both on the aquatic environment and humans (Makepeace et al., 1995; Eriksson et al., 2007; Gasperi et al., 2012; Zgheib et al., 2008; Ingvertsen et al., 2011; Madrid and Zayas, 2007; Paschke, 2003). The concentration of TSS could vary significantly depending on the place of origin (e.g. for streets: TSS ranges from 61 to 320 mg/L; for parking: TSS ranges from 42 to 240 mg/L; and for motorways: TSS is around 200 mg/L (Boogaard, 2015)). It must also be considered that very often TSS are constituted or covered by organic matter which works as a binding material for the sorption of the above-mentioned emergent pollutants, allowing, therefore, their transport even on a long distance. Therefore, retention of suspended solids has been a primary function of many of the NBS. Typically, CWs can remove up to 88% of TSS, 92% of BOD5, 83% of COD even after 20+ years of operation (Vymazal et al., 2019). For the nutrients, the removals vary greatly between the systems and are in range of 46-90% for total phosphorus and 16-84% for total nitrogen (Malaviya and Singh, 2012).

In addition to the removal of traditional pollutants such as suspended solids, organic matter and nutrients (Arden and Ma, 2018; Machado et al., 2017; Zhang et al., 2014), CWs are capable of removing organic and inorganic pollutants (Krzeminski et al., 2019; Verlicchi and Zambello, 2014). Among these, the removal of pesticides (Barceló and Petrovic, 2008), heavy metals (Wang et al., 2017), pharmaceuticals (Li et al., 2014; Zhang et al., 2014; Zraunig et al., 2019), and various other contaminants of emerging concern (CEC) (Gorito et al., 2017; Talib and Randhir, 2017; Imfeld et al., 2009; Matamoros et al., 2010) have been explored in the last decade. The observed removal of heavy metals was between 23-97% depending on the heavy metal, CWs type, type of water matrix and others (Malaviya and Singh, 2012).

Regarding the CECs, plant-associated NBS have been reported to be crucial for the removal of different CECs (Carvalho et al., 2014; Yang Zhang et al., 2016) which can favour the solutions bringing more “green” in the cities. Therefore, the key removal pathways are the uptake by plants (e.g., carbamazepine), microbial degradation (e.g., ibuprofen, salicylic acid, galaxolide), adsorption and subsequent sedimentation (e.g., triclosan, tetracycline), and photodegradation (e.g., ketoprofen, naproxen, triclosan, diclofenac) (Bi et al., 2019).

Although treatment wetlands can achieve high removal of up to 100% of different organic and inorganic chemicals, the removal effectiveness varies significantly and the removal effectiveness of particular compounds may vary depending on the CW design, its operation mode and seasonal conditions (Krzeminski et al., 2019; Verlicchi and Zambello, 2014; Yang Zhang et al., 2016; Zraunig et al., 2019). This indicates that for efficient removal, CWs needs to be designed and/or adjusted for targeted pollutants. While CWs can be very effective, they are not able to completely remove CEC from the (waste) water. Moreover, hybrid systems combining different types of CWs, or other treatment techniques, might offer increased removal due to the synergistic effects against specific types of pollutants (Garcia-Rodríguez et al., 2014; Ilyas and Masih, 2017; Verlicchi and Zambello, 2014; Zhang et al., 2014; Ying Zhang et al., 2019). Furthermore, treated water from TWs may be suitable for some reuse applications if well designed and maintained (Arden and Ma, 2018; Ilyas and Masih, 2017; Krzeminski et al., 2019). Nevertheless, current knowledge gaps restrict holistic evaluation of CWs applicability and the estimation of CWs potential for the removal of CEC.

Regarding the climatic conditions, CWs have been demonstrated to work efficiently in different climatic conditions but tropical conditions tend to favour treatment performance due to continuous plant growth, extended sunlight exposure and increased microbial activity, being of particular importance for more recalcitrant pollutants (Machado et al., 2017; Zhang et al., 2014). However, good comparable removal rates of suspended solids, organic matter, and phosphorus are reported for temperate conditions, with only nitrogen removal being affected in the cold climate (Wang et al., 2017).

For urban water pollution control other NBS (and green infrastructure elements) can be very effectively used in combination with the CWs for purposes such as the wastewater source control and separation, water reuse and other means of sustainable sanitation framework (Masi et al., 2018). Accordingly, one of the key concepts could be a combination of composting and vermicomposting toilets (Anand and Apul, 2014; Hill and Baldwin, 2012) and greywater treatment with wetlands or green walls providing the treated water for further reuse. Furthermore, as the space in cities becomes a highly valuable commodity, multipurpose nature-based solutions offering other benefits beyond the water treatment and pollution control becomes a viable alternative (Frantzeskaki, 2019; Raymond et al., 2017). Multifunctionality is a key factor, as the water pollution control does not have to be the major role of NBS but can be integrated into stormwater management and biodiversity enhancement.

3.4. Projects / Case studies approach

In spite of the different potential for implementation of NBS for urban water management, the showcased projects from the COST action members are only dealing with stormwater management. The applications range from rainwater harvesting in water-scarce areas (e.g. HYDROUSA project in Greece) to the reforestation of watersheds (e.g. Rangárvellir project in Iceland (Keesstra et al., 2018)). While both aforementioned cases aim at re-establishing the natural water cycle and increasing natural water retention, the means and purposes differ. Moreover, the Natural Water Retention Measures project, directed by The EU Directorate-General for Environment from 2013 to 2014, aimed for improving the water status on hydromorphology and diffuse pollution, by offering a catalog of case studies showcasing a broad range of concepts and case studies (nwrm.eu, 2015). However, for effective selection of NBS for stormwater management planning, instruments are still needed. Within project Concepts for urban rainwater management, drainage and sewage systems (KURAS) in Germany, an integrated planning approach for stormwater management measures was developed considering the other aspects of NBS besides water retention (Matzinger et al., 2017). The potential multi-functionality of NBS is an important feature, especially regarding the implementation in circular cities. The Gorla Maggiore water park project in the Northern Territories of Italy, which includes the use of a water park for NBS applications and Integrated and Sustainable management service for water-energy cycle in urban drainage systems (G.I.A.R.E.) project in the Southern of Italy is based on water-energy interaction in Milan, Italy are also summarized in this section. In addition to these two Italian projects, the C2C-CC project, which is carried out in Denmark and includes flood control, water treatment, base-flow and sustainable heat energy applications, is summarized in the section. The main purpose of explaining these five projects here in this section is to emphasize the representative of multipurpose NBS implementations for stormwater management.

3.4.1. Project 1: The Gorla Maggiore water park

The Gorla Maggiore water park project, located in Gorla Maggiore, Northern Italy, is an urban wetland becoming a place for NBS and ecosystem services (Figure 4). The park aims at protecting the city against flooding, improving water quality, increasing biodiversity and obtaining social co-benefits (Rizzo et al., 2018). The park, with a total area of approx. 3 ha, comprises of sections with different functionalities: 1) stormwater detention for flood prevention (1 ha); 2) domestic water treatment (0.4 ha); and 3) recreational areas (1.3 ha). Furthermore, the combined sewer overflow and excess runoff may be diverted into the park in case of extreme rainfall events, with an expected reduction of peak flow by 86% and downstream discharge of 8,900 m^3 for events with a 10-year return period. Moreover, it reduces the downstream dissolved organic carbon load for 11.7 t/yr and nitrogen load for 0.4 t/yr, along with social and ecological benefits (Masi et al., 2017). In addition, the project demonstrates that the performance and costs of the park are similar or even better than the grey infrastructure for water purification and flood protection (Masi et al., 2017).

Figure 4: The Gorla Maggiore water park (Source: naturvation.eu,2019)

3.4.2. Project 2: Coast to Coast Climate Challenge (C2C-CC project)

The C2C-CC project (http://www.c2ccc.eu/) is a Danish cross-municipality climate adaptation projects which 31 partners and 19 supportive partners work to create a climate resilient Central Region in Denmark. The sub-project "Infiltration of surface water through permeable coating" has the primary aim of re-establishing the natural pre-development water cycle and prevent flooding. This is done by harvesting rainwater in the roadbed as the road is made of permeable asphalt. The roadbed is constructed using a gravel mix ensuring a porosity of 30% which can detain the volume of water generated by a 100-year-flood. Moreover, the gravel mix removes Total Suspended Solids (TSS) and heavy metals from the water. Subsequently, the detained water transmits its heat to a geothermal tube, with a length of 800 meters, connected to a nearby day-care centre for heating, which is then infiltrated into the soil (Figure 5). Thus, this NBS provides flood control, water treatment, base-flow and sustainable heat energy.

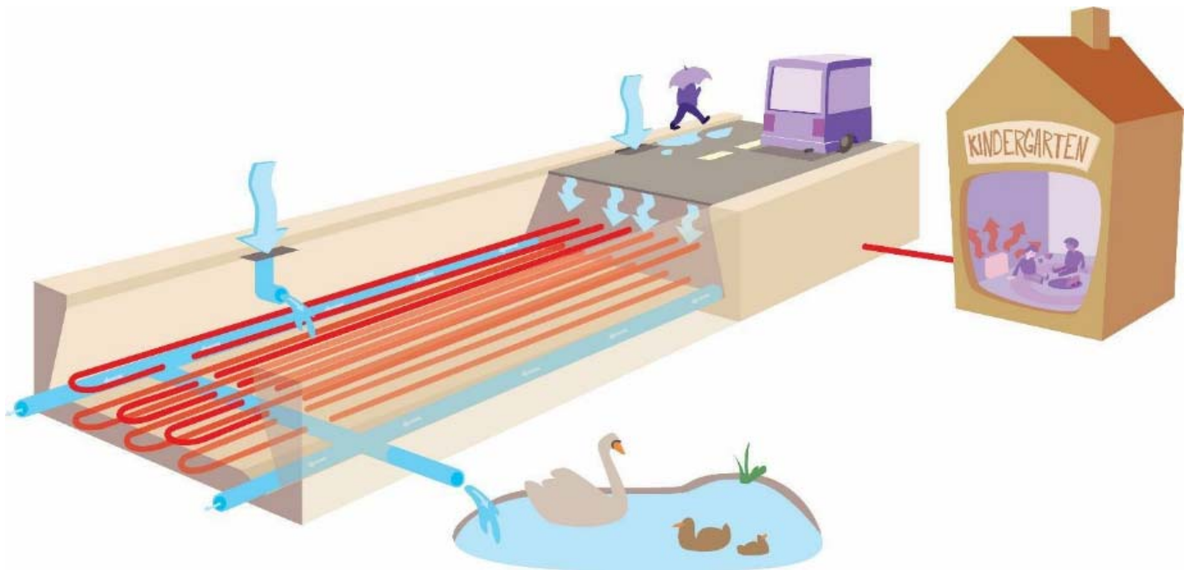

Figure 5: Sketch showing the principles behind the infiltration of surface water through the permeable coating project (Source: VIA University College,2017)

3.4.3. Project 3: HYDROUSA

HYDROUSA aims to revolutionize the water supply chain in Mediterranean regions by demonstrating innovative solutions for water/wastewater treatment and management, which will close the water loops and will also boost their agricultural and energy profile. Relevant to NBS applications, HYDROUSA demonstrates that circular NBS technologies work for wastewater treatment and nutrient recovery, while creating further environmental and societal benefits. The project offers a solution for the problem which is about the rare water reserves in Mediterranean region during the summer period with the high tourist season. The project will not only develop and demonstrate innovative water services, but also will revolutionise the water value chains in Mediterranean areas from water abstraction and use up to sewage treatment and reuse (www.hydrousa.org, 2019). There are five water categories in HYDROUSA project: rainwater, groundwater, wastewater, water vapour and sea water and the systems defined between these categories are harvesting, recharge and restore, wetlands, vapour condensation and tropical greenhouse. Moreover, biomimicry design concepts and fertigation are being applied to increase the efficiency of the selected nature-based solutions. Some of the recovered products of these systems are water for domestic use, irrigation water, biogas, drinking water and salt (Figure 6).

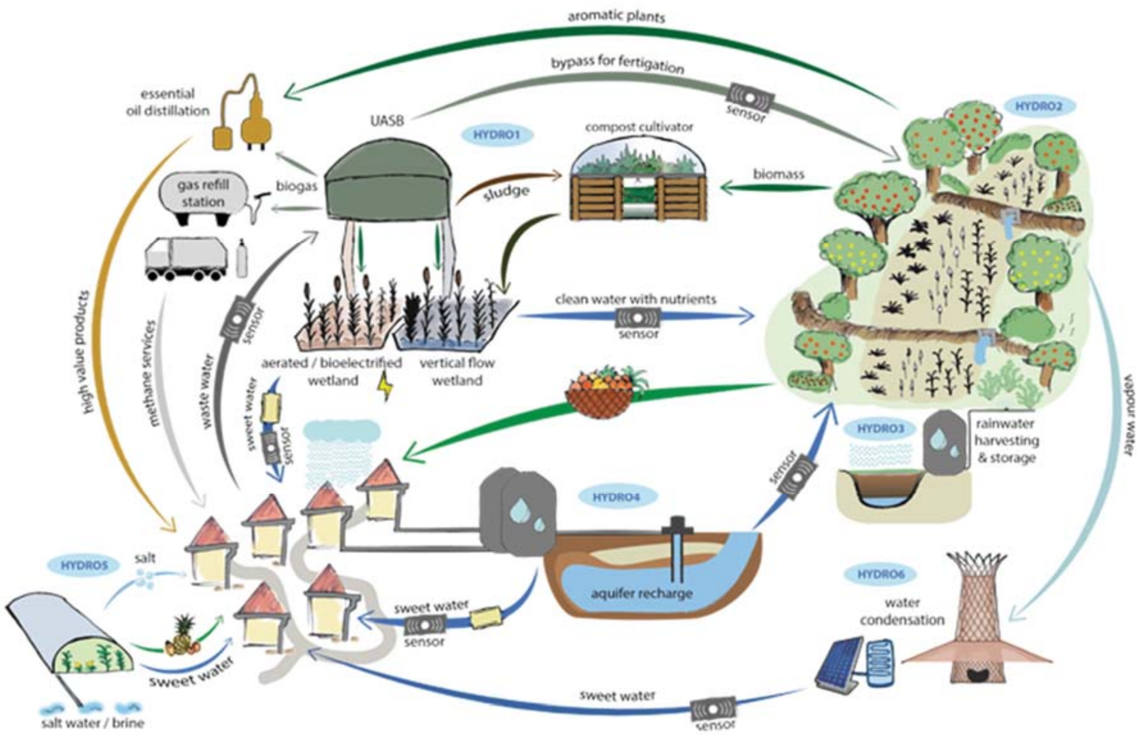

Figure 6. The HYDROUSA project working principles and the processes (from www.hydrousa.org, 2019).

3.4.4. *Project 4: Concepts for urban rainwater management, drainage and sewage systems (KURAS)*

The aim of this project is to give the answer of the question "How the future wastewater discharge, water quality, urban climate and quality of life in the city can be improved through intelligently coupled storm water and waste water management ?". The project consists of a network of partners from research and industry as well as the city of Berlin decision makers. KURAS is the elaboration and exemplary demonstration of integrated concepts for a sustainable handling of wastewater and rainwater for urban locations. As mentioned in the introduction section, NBS aim to protect, sustainably manage, and restore natural or modified ecosystems. The KURAS project aims to decrease the water consumption after having the heavy rainfall in the city and enables the sustainable management them. Some of the following sub-goals, which defined to reach this achievement are as follows (www.watershare.eu, 2019):

- For wastewater disposal companies and operators of municipal sewer networks, which, like Berlin, have a slight gap, options for the adaptation of wastewater infrastructure to climate change and its consequences are being developed.
- Prognosis models are intended to investigate the effects of measures - e.g. to avoid deposits in the sewer system after long periods of dry weather or of mixed water overflows in waters during heavy rainfall - for real Berlin model areas.

Figure 7 presents the main research focus of the study.

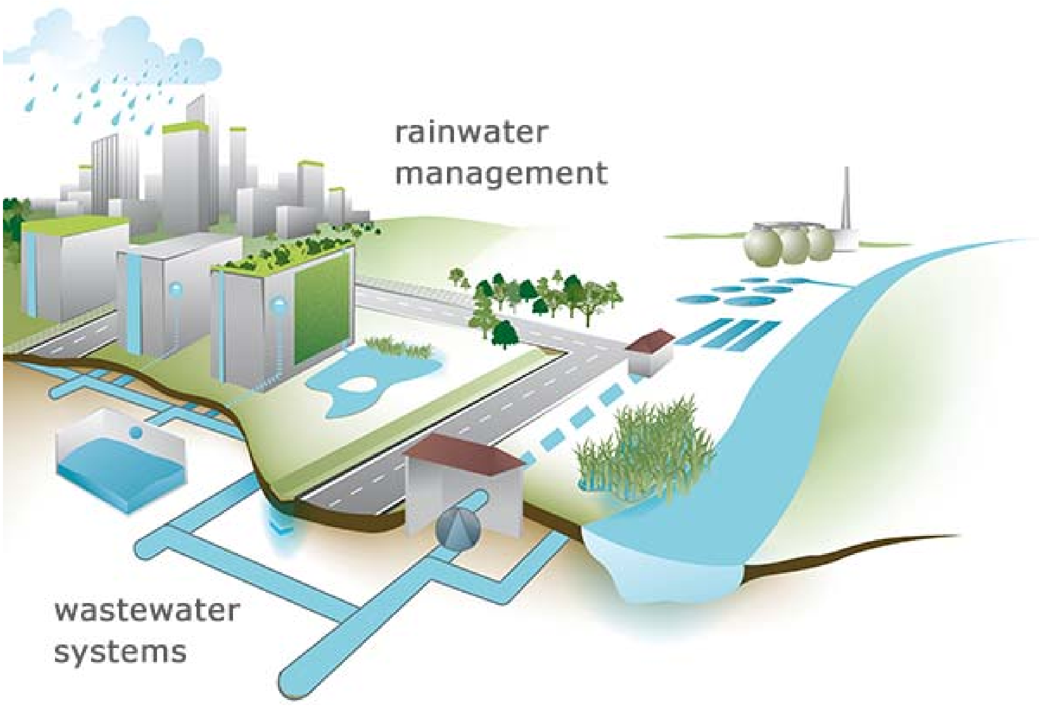

Figure 7. Research focus of KURAS project (Source; https://nawam-inis.de/en/inis-projects/kuras, 2019)

3.4.5. Project 5: Integrated and Sustainable management service for water-energy cycle in urban drainage systems (G.I.A.R.E.)

The main objective of the project, relevant with the aim of NBS, was to develop an integrated approach for a sustainable water-energy cycle management in the urban context.In this perspective, a technological platform was implemented in order to both optimize the use of water resources that insist on the urban drainage network such as meteoric waters deriving from the roof of buildings (40% of total urban area) and paved areas, i.e. roads, yards, etc., (35%) and to allow energy saving (Figure 8). For these purposes, experimental activities were conducted on:

- Control of inflows to the drainage network;
- Control of the polluting load generated;
- Thermo-energy benefits;
- Potential of rainwater for reuse.

Specific objectives of the Project (Figure 8) were listed as follows:

· OR1: "Realization of a compact storm drain prototype device for the treatment of run-off rainwater";
· OR2: "Module for management and optimization of water - energy performance of green roof systems in Mediterranean climate";
· OR3: "Urban drainage planning and design service through sustainable technologies to reduce inflows and pollutants";
· OR4: "Development of a technological platform for decision-making support for the integrated and sustainable management of the water-energy cycle in the urban drainage system".

"Urban Hydraulic Park" was constructed as a demo site at the Vermicelli catchment (University of Calabria) where green roof with a rainwater harvesting system, permeable pavement, a stormwater filter and a traditional sedimentation tank were connected to a treatment unit. Further, monitoring and acquisition system was used to analyze the environmental benefits and the hydraulic and thermal efficiency of each unit.

The results of the Project showed a good hydraulic performance of the green roof concerning the stormwater retention faced in Mediterranean weather conditions (Piro et al., 2019a; Palermo et al., 2019). The hydraulic behavior of the green roof, permeable pavement and the stormwater filter were also analyzed by means of a modelist approach (Brunetti et al., 2016; Garofalo et al., 2016; Brunetti et al., 2017; Piro et al., 2019b). Moreover, the Life Cycle Assessment (LCA) analysis of the green roof and permeable pavement highlighted the sustainability of these low-impact infrastructures (Maiolo et al., 2017).

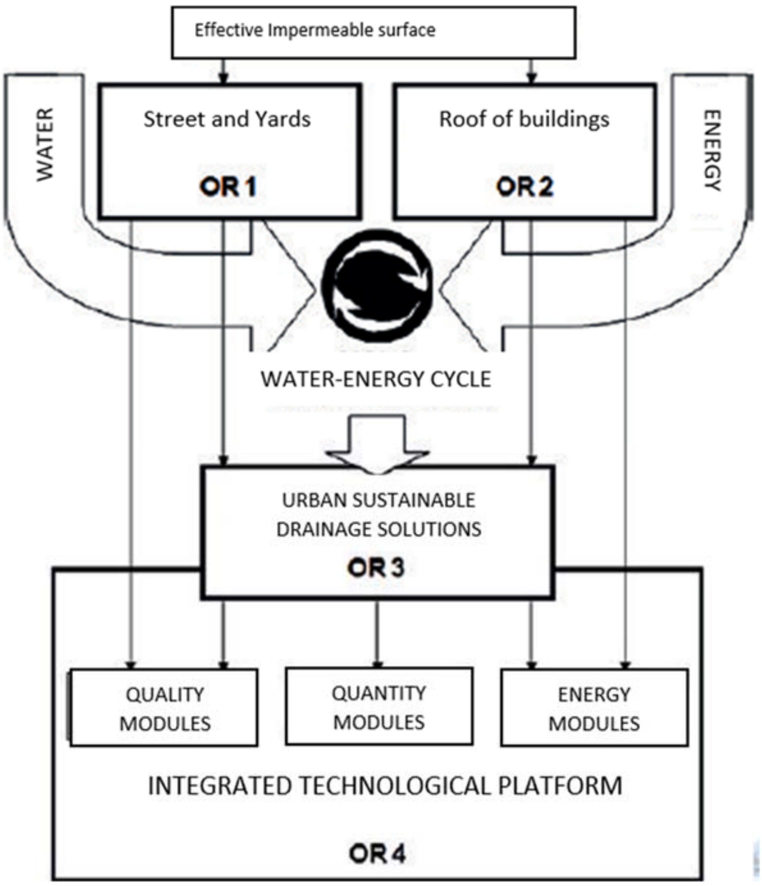

Figure 8. The working principle of G.I.A.R.E project (from www.giare.eu, 2019)

3.5. Discussion and concluding remarks

Based on the presented literature review and case studies, three main focuses of NBS implementation could be identified: i) stormwater management, ii) water-food-energy nexus using water for food and energy production, and iii) water pollution control. The presented overview demonstrates that NBS are not only effective and efficient, but also have a big acceptance by people neighbouring such facilities.

Water is a fundamental resource for three main components necessary for human civilization; i) drinking water; ii) food production; and iii) energy production. In some cases, NBS can generate all three components in urban areas. Nevertheless, it is challenging to balance the production of water with given characteristics, food, and energy in a sustainable way, ensuring sufficient supply of all three products.

It is a fundamental task for the scientific community to provide evidence-based facts on NBS and include blue-green infrastructures in order to promote sustainable water management policies. The presented review and NBS projects demonstrate the advantages of NBS both in social and economic terms, i.e. creation of new jobs and saving of energy and resources. Closed-loop recycling of greywater can decrease the amount of waste water by up to 50-60%, reducing sewage treatment costs at centralized WWTP. Other projects have focused on NBS and the water-food-energy nexus, as summarised in Supplementary Material Tables. Hence, NBS include constructed wetlands, restored wetlands, coastal Mediterranean wetlands, green walls, and green roofs (Figure 9). The NBS acts as groundwater storage, water retention, water purification and improvement of environmental value.

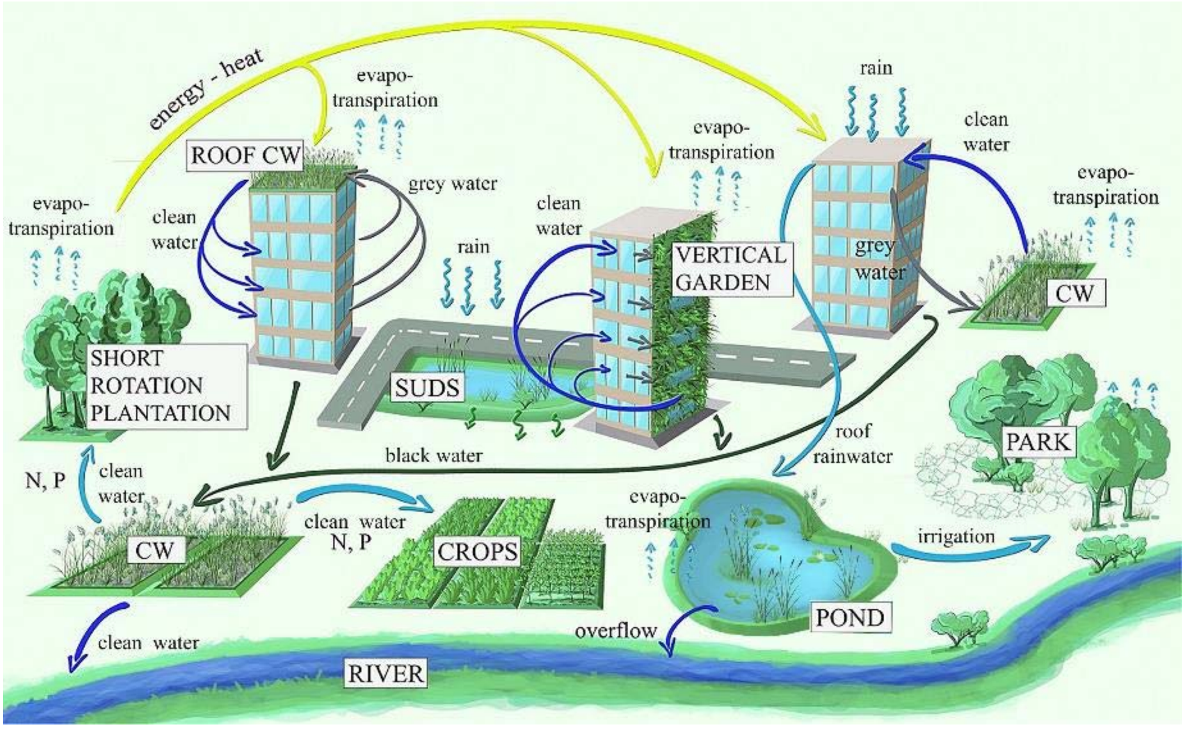

Figure 9. Advisable scheme of sustainable water management in an urban settlement with diffusely integrated NBS (SUDS: Sustainable Drainage Systems, CW: Constructed Wetlands) (Extracted from Masi et al., 2018).

The most frequent NBS are treatment wetlands, which can remove nutrients and organic components, including organic micropollutants and other emerging compounds. They can be designed for water sources with very different characteristics. In addition to treating water for a particular purpose, wetlands can be designed for water storage, infiltration and evapotranspiration, important functions of the urban water cycle. They also provide a series of additional benefits that grey infrastructure cannot, such as providing ecological niches within urban areas, or preferred recreation and educational areas. However, most of the research and technical development of treatment wetlands historically relates to decentralized treatment, normally away from urban areas. Thus, we still have only a small number of examples and limited data on the implementation of treatment wetlands in the urban environment. In spite of the potential of other NBS implemented in the urban area, such as green walls or SuDS, to purify water, the majority of the existing examples and publications deal only with the attenuation of the heat island effect or stormwater management, respectively. It is thus clear that for increasing the implementation of NBS in the urban environment, further research and demonstration should more effectively combine different disciplines and needs in aligning with the holistic perspectives required by the water-food-energy nexus and taking into consideration the ecosystem services provided.

The implementation of NBS applications in urban areas is, at the same time, limited by some challenges. For instance, especially in densely built urban areas or protected historical city centers, the limited space available is a major drawback. Nevertheless, while this represents a present challenge in the future architecture and urban planning can be adapted to more easily accommodate NBS, which provide the widest range possible of benefits. In fact, NBS present a multifunctional capacity for resource recovery and pollution control, delivering multiple benefits in this issue, though it is worth noting that NBS for urban water management clearly address other challenges, such as biodiversity enhancement and a more efficient management of the water-food-energy nexus, among others.

The presented NBS projects are representative examples that highlight the superior effect of NBS over conventional water management solutions. Stormwater management can be implemented by establishing water parks with extended retention basins that withhold rainwater during heavy precipitation events as illustrated in the example of Gorla Maggiore in northern Italy (Figure 4). Such water parks offer protection from floods but also create ecosystems within the cities. Moreover, permeable coating of streets and paths are another way of reducing flood risk in cities. These systems can also produce energy for district heating by simply using the heated surface of paved streets and paths. The Danish project C2C-CC is an illustrative example of such a system. The HYDROUSA project investigates options for NBS to manage water resources on Greek islands which experience an increased water demand during the touristic season. The KURAS project in Berlin, Germany, focuses on NBS for stormwater and wastewater management in large urbanized areas. Water parks, permeable coating of streets and green roofs function as water retention reservoirs, slowing down the runoff process during heavy precipitation events. In some cases, the water stored in these NBS can become available at later points during the lack of precipitation periods, thereby reducing the drought effects. The G.I.A.R.E. in Italy focuses on integrated and sustainable management service for water-energy cycle applications**.**

In the future, the reliance on NBS in sustainable water use is expected to increase. Given the still-increasing effects of climate change, it is necessary that in the future, planning for city infrastructure will be based on climate change mitigation, adaptation and resilience. The most common applications for NBS will be in parallel with integrated river management practices and re-establishment of wetlands. The developments towards more holistic concepts of resources flow management, imply integrated, cross-sectoral systems and approaches. In the context of urban water management, pollution control is shifting towards resource recovery. The traditional separation between water supply, wastewater, and stormwater is challenged towards reusing properly treated wastewater and stormwater for purposes where potable water quality is not necessarily needed. NBS implementation can support this paradigm shift.

Based on the presented literature review, the NBS case studies and the discussion above we conclude the following:

1. NBS help mitigate flood and drought impacts simultaneously supporting stormwater and water supply management.
2. NBS are essential to maintain the natural hydrologic regime despite development and partial sealing of surfaces, not least to keep the natural water cycle of evapotranspiration and rainfall,

but also to mitigate urban heat island effects and allow the growth of urban green with local water resources.

3. NBS can efficiently purify very different water sources, greywater, rain water, sewer overflow or wastewater, for various purposes of further use, while generating numerous side benefits. Besides treating water NBS can also retain stormwater, produce or irrigate food and save energy.
4. NBS create very promising new opportunities to use water more effectively and efficiently, enable urban farming or mitigate energy consumption. However, the urban water-food-energy nexus is still in a very early stage of development.

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4. WG3 review paper

A review of nature-based solutions for resource recovery in cities

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Abstract

Our modern cities are resource sinks designed on the current linear economic model which recovers very little of the original input (e.g. nutrients, materials, energy and water). As the current model is not sustainable in the medium and long term, a viable solution is to recover and reuse part of the input. In this context, resource recovery using nature-based solutions (NBS) is gaining popularity worldwide. In this specific review, we focus on NBS as technologies that bring nature into cities and

those that are derived from nature, using (micro)organisms as principle agents, provided they enable resource recovery. The findings presented in this work are based on an extensive literature review, as well as on original results of ongoing and recent research and innovation projects across Europe. The case studies were collected by participants of the COST Action Circular City, which includes a portfolio of more than 92 research projects. Based on discussions within the working group, the present review article focuses on urban wastewater, industrial wastewater, municipal solid waste and gaseous effluents, the recoverable products (e.g. nutrients, nanoparticles, energy), as well as the implications of source-separation of waste and end-of-pipe technologies vs. circularity by design. The analysis is complemented by an assessment of the maturity of different technologies (Technology Readiness Level) and the barriers that need to be overcome in order to accelerate the transition to resilient, self-sustainable cities of the future.

Keywords

Nature-based solutions, circular cities, resource recovery, nutrients, energy.

Abbreviations / acronyms

AD	Anaerobic digestion	MBT	Mechanical Biological Treatment
ALE	Alginate-like exopolysaccharides	MFCs	Microbial Fuel Cells
ATAD	Autothermal Thermophilic Aerobic Digestion	MSW	Municipal Solid Waste
Bio-W	Bio-waste	N	Nitrogen
BIQ	Bio-Intelligent Quotient	NBS	Nature-based solutions
BOD	Biological Oxygen Demand	OLAND	Oxygen-limited autotrophic nitrification/denitrification
BW	Blackwater	P	Phosphorus
CDW	Construction and demolition waste	PBR	Photobioreactor
COD	Chemical Oxygen Demand	PCB	Polychlorinated biphenyl
CSTR	Continuously Stirred Tank Reactor	PHA	Polyhydroxy-alkanoates
CW	Constructed Wetland	PHB	Polyhydroxybutyrate
DTM	Dry toilet matter	PPB	Purple Phototrophic Bacteria
ESCO	Energy Service Companies	R&D	Research & development
EWS	Evapotranspirative Willow System	RO	Reverse Osmosis
FGD	Flue Gas Desulfurisation	TRL	Technology Readiness Levels
FW	Food waste	TS	Total Solids
GHG	Greenhouse gas	TSS	Total Suspended Solids
GDP	Gross Domestic Product	UASB	Upflow Anaerobic Sludge Blanket
GrW	Green waste	VFAs	Volatile Fatty Acids
GW	Greywater	VFY	Vegetable, fruit and yard waste
HRAP	High-rate algae ponds	VSS	Volatile Suspended Solids
K	Potassium	WW	Wastewater
LCFA	Long chain fatty acids	WWTP	Wastewater Treatment Plant
MBR	Membrane Bioreactor	YW	Yellowwater

4.1. Introduction

Cities are emerging as centres of human and economic capacity, with 54% of the global population living in cities and raising 85% of worldwide GDP (World Bank 2017). However, cities also accumulate or emit end-user resources and wastewater, functioning as resource sinks within the current linear economic model of 'take-make-dispose'. Urban populations consume 75% of natural resources, they are responsible for 50% of global waste and for 60-80% of overall greenhouse gas emissions (Ellen MacArthur Foundation 2017a). Given the human and economic potential, the accumulation of resources and societal challenges of ecosystem degradation present in urban areas, the momentum is shifting towards recovery of these resources within the urban infrastructure.

Resource flows are generally considered "waste", destined for final disposal as soon as they reach sewage systems, rubbish bins and exhaust pipes, although they include valuable resources such as nutrients (N, P, K), organics, water, and metals. Each year, Europeans produce 3.6 Mt of N, 1.7 Mt of P, and 1.3 Mt of K as part of human excrements. At the same time, Europe consumes 11 Mt of N, 2.9 Mt of P, 2.5 Mt of K of manufactured fertilisers (Fertilizers Europe 2017). The volumes of post-use material bear high potential. Therefore, the present study considers secondary resource streams, including urban wastewater, industrial wastewater, municipal solid waste and gaseous effluents, as well as the potential of source-separated waste(water) streams. Figure 1 showcases the urban water, nutrient, material and energy loops that can be made intact by using and integrating NBS in cities.

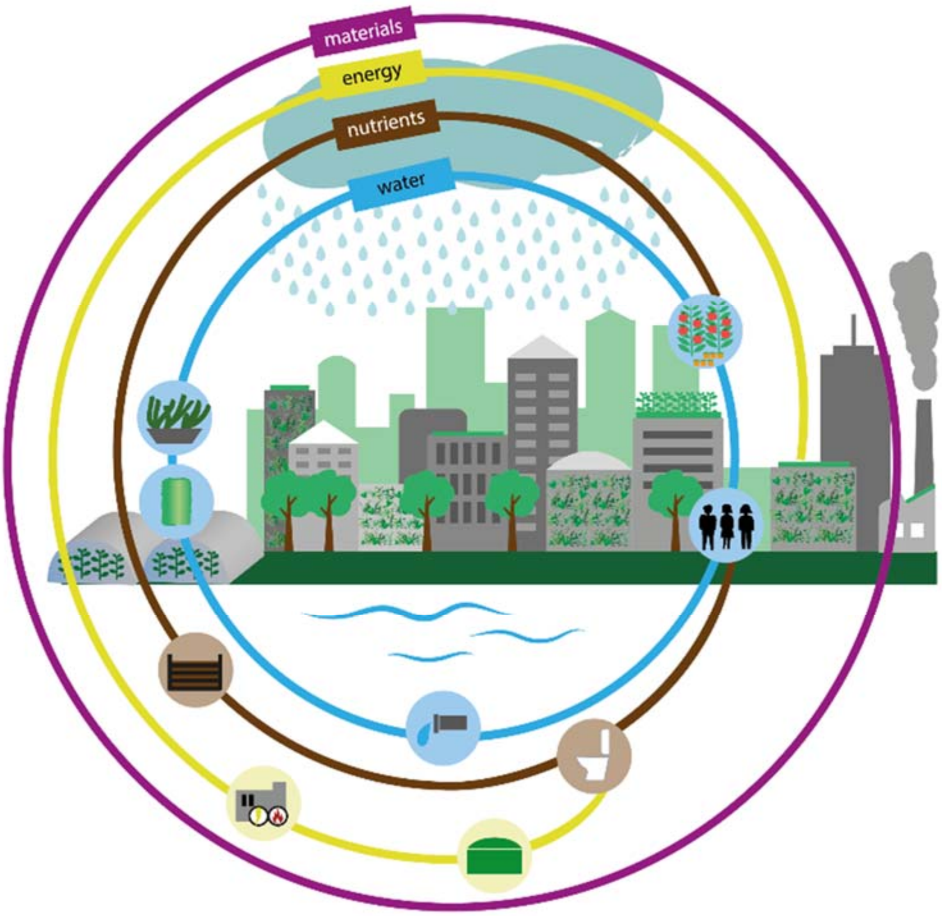

Figure 1: Overview of urban water, nutrient, material and energy loops enabled using NBS within cities

The present paper is a product of interdisciplinary cooperation among researchers from all 28 EU countries and 11 third countries within the EU-funded *COST Action Circular City*. Discussions among project members have produced a definition of nature-based solutions (NBS) for the purpose of the COST Action, set out in Langergraber et al. (2019). As such, the present paper defines NBS as technologies that bring nature into cities and those that are derived from nature, using *organisms as principle agents* if they enable resource recovery and the restoration of ecosystem services in urban areas. The objective of this review is to provide a comprehensive overview of nature-based solutions (NBS) applied and developed today to recover resources in cities, along current cutting-edge research and innovation, and to map out recoverable products as well as barriers, which represent the scope for further research. NBS can be applied to micro (household), meso (district) and macro (city and above) scales (ibid).

The findings are based on a literature review, as well as on the review of ongoing and recent research and innovation projects. These case studies were collected by participants of the *COST Action Circular City* with a portfolio of total 92 research projects, as well as projects that partner researchers are aware of. Case studies specifically mentioned in the paper illustrate the diversity of applications and recoverable products. Based on discussions within the Action's working group on *resource recovery*, the present review paper looks at urban wastewater, industrial wastewater, municipal solid waste and gaseous effluents, as well as the implications of source-separation of waste and end-of-pipe technologies versus circularity by design. Non-technical interrelated factors, which influence the applicability, selection and adoption of available technologies, such as legal frameworks, community awareness, acceptance and involvement, business and financing conditions, are not addressed here but are discussed in a separate review paper (Katsou et al. 2019).

4.2. Resource Streams and Opportunities for Recovery in Cities

The following section reviews different secondary resource streams found in cities, subdivided in urban wastewater, industrial waste and wastewater, municipal solid waste, gaseous effluents and source-seperated waste. It provides an overview of technologies, projects and developments as well as barriers in relation to resource recovery with NBS.

4.2.1. Urban Wastewater

Urban wastewater is defined as domestic wastewater or its mixture with industrial wastewater and/or runoff rainwater (European Commission 1991). The adequate treatment of urban wastewater is essential to protect human health and the environment. In Europe, cities largely collect and treat urban wastewater as a mixture of grey and blackwater, often also stormwater (combined sewer system). In Europe, more than 277 million people live in agglomerations bigger than 150,000 population equivalent (PE). They produce 41.5 million m^3 of wastewater per day. Currently, an annual 2.4% (1 billion m^3) of treated urban wastewater effluents are reused in the EU (European Commission 2018b), but this secondary resource stream bears significantly more resources to recover, including nutrients, organic carbon, lipids, biosolids and energy. The vast majority is still unexploited, but many of these can be recovered in cities using NBS. Table 1 below provides an overview of projects deriving secondary resources and products from unsegregated urban wastewater, including reclaimed fertigation/irrigation water (water and nutrients), P-rich sludge, biopolymers, alginates, cellulose, construction material and energy (biogas, biofuel, electricity and heat). Information on the scale at which the technology is applied, the TRL, region, project and project periods provide an indication as to the transferability of applied technologies.

Table 1. Overview of resources that can be recovered from unsegregated urban wastewater, recovery technologies applied, recovered products, scale, TRL, region and project.

Recoverable resource	Technologies applied	Products	Scale	TRL	Region	Project	Project period	Reference
Reclaimed water, energy & nutrients	Upflow anaerobic sludge blanket (UASB) + constructed wetlands + UV disinfection	Fertigation water; domestic non-potable water	micro, meso	7	Lesvos Island, Greece	HYDROUSA	2018-2022	https://www.hydrousa.org/
	Combination with shred kitchen waste, liquid-solid separation, green walls, anaerobic membrane bioreactor (AnMBR), UV hygienisation	Fertigation water; biogas, fertiliser, domestic non-potable water	micro	7	Austria, Spain	HOUSEFUL	2018-2022	https://houseful.eu/
	Hybrid constructed wetland, evapotranspirative willow system with zero discharge, algae-based technology	Fertigation water, woodchips for heat production	micro, meso	7	Slovenia	GreenT (Slovenian Research Agency J2-8162 and Z2-6751)	2017-2020	http://www2.zf.uni-lj.si/si/component/content/article/32-raziskovanje-splosno/2489-zapiranje-snovnih-poti-pri-ciscenju-komunalnih-odpadnih-voda-z-zelenimi-tehnologijami-j2-8162
Nutrients	Adsorption columns and planted filters	Nutrients for irrigation water	micro	3-4	Barcelona & Almería, Spain	INCOVER	2019-2021	https://incover-project.eu/technologies/nutrient-recovery
Organic carbon (carbo-hydrates)	Two-stage anaerobic-photosynthetic High Rate Algae Pond system.	Biopolymers	micro	6	Chiclana de la Frontera & Almería, Spain	INCOVER	2019-2021	https://incover-project.eu/technologies
	Two sequencing batch reactors (SBR): one for heterotrophic bacterial growth and the other for growth of autotrophic nitrifiers	Biopolymers (PHA) and P-rich sludge	macro	6	Manresa, Spain	SMART-Plant	2016-2019	http://www.smart-plant.eu/
	Mixed microbial cultures, activated sludge at WWTP, bioprocess facilitating feast and famine conditions, biomass is fed with VFA-rich liquors, pure acetic and propionic acids	Biopolymers (PHA)	meso	6-7	Netherlands	Phario	2015-2019	http://phario.eu/
	Alginate extraction from granular excess sludge from 3 municipal Nereda® -plants and one industrial one	Alginates	macro	6	WWTP Epe, Dinxperlo, Vroomshoop, Netherlands	National Alginate Research Programme	2013-2019	https://www.royalhaskoningdhv.com/en-gb/news-room/news/water-authorities-working-hard-to-achieve-circular-economy/7123

	Alginate extraction from Nereda®-granular excess sludge	Kaumera Nereda® Gum (formerly: Neoalginate)	macro	7-8	WWTP Zuthpen, Netherlands	KAUMERA	2016-2018	https://kaumera.com/english/
Lipids	Two-stage aerobic/ anaerobic reactor, M. parvicella bacterium accumulates FOG (fat, oil, grease), lipids extraction, subsequent esterification/ transesterification	Biofuel	micro	3-4	Luxembourg & France	WOW	2018-2021	https://www.cell-vation.com/wow-project
Energy, nutrients	Anaerobic biofilter for municipal wastewater treatment	Biogas	meso, macro	7	Karmiel, Israel	SMART-Plant	2018- 2020	http://www.smart-plant.eu/
	UASB for municipal wastewater	Biogas	meso	7	Sweden	Pioneer-STP	2016-2019	https://www.kt.dtu.dk/english/research/prosys/projects/pioneer-stp
	Vacuum toilets and collection, AD Fixed bed reactor, heat exchange, district heating	Biogas, fertiliser, thermal energy	meso	7-8	Hamburg, Germany	Hamburg Water Cycle, Jenfelder Au	2011-2018	https://www.hamburgwatercycle.de/en/the-jenfelder-au-neighbourhood/the-hwc-in-the-jenfelder-au/
Energy	Horizontal subsurface CW with electrodes; oxidation of the organic matter generates electricity	Electricity	micro	4-5	Spain, UK, Turkey	URBAN GreenUP	2017-2022	https://www.urbangreenup.eu/
Energy, salts	Microbial desalination combined with membrane treatment	Freshwater, treated wastewater	micro, meso	5	Spain, Chile, Tunisia	MIDES	2016-2020	http://midesh2020.eu/
Nutrients, lipids, cellulose	Microbial conversion of nutrients to high-value compounds in a biorefinery approach	Ectoine, PHA, biogas, cellulose, construction materials	meso, macro	6	Spain	DEEP PURPLE	2019-2023	https://deep-purple.eu/

DEEP PURPLE: Conversion of diluted mixed urban bio-wastes into sustainable materials and products in flexible purplephotobiorefineries
GreenT: Closure of material pathways in urban wastewater treatment with green technologies
HYDROUSA: Demonstration of water loops with innovative regenerative business models for the Mediterranean region
INCOVER: Innovative Eco-Technologies for Resource Recovery from Wastewater
MIDES: Microbial Desalination for low energy drinking water
Pioneer STP: The Potential of Innovative Technologies to Improve Sustainability of Sewage Treatment Plants
Run4Life: Large scale nutrient recovery from domestic wastewater
SMART plant: Scale-up of low-carbon footprint Material Recovery Techniques in existing wastewater treatment PLANTs
WOW – Wider business opportunities for raw materials from wastewater

Technologies and products

As set out in Table 1, NBS for resource recovery from urban wastewater range from extensive technologies, such as constructed wetlands, evapotranspirative willow systems and algae ponds, to high-tech biological processes, such as rotating biological contactors, aerobic granulation (Nereda®) and anaerobic reactors. The wide range of recoverable products includes commonly derived products, such as biogas from primary and secondary sludge and reclaimed water for agricultural (crop irrigation or fertigation), industrial (cooling water), residential (sanitary flushing) and urban (park irrigation or even crop production) purposes as well as for groundwater recharge.

Combustible biomass of plants and microalgae can be converted to biogas and digestate for use as fertiliser through anaerobic digestion, bioethanol through sugar fermentation or ethylene reaction with steam (EUBIA 2019), biochar through pyrolysis, or processed for pulp-paper production or bioplastics. Bio-oil is produced by processing biomass under high temperature without oxygen and biohydrogen by steam reformation of bio-oils, dark and photo fermentation of organic material as well as photolysis of water catalysed by specific microalgae species (Li et al. 2008). Algae biomass can also be used for feed production and extraction of high-value chemicals (Passos, Astals, and Ferrer 2014; Razzak et al. 2013; Wuang et al. 2016; Fermoso 2019).

Constructed wetlands and nutrient-rich irrigation

Urban wastewater contains nitrogen and phosphorus which is usually not valorised within wastewater treatment plants (WWTPs). Although raw urban wastewater is a diluted effluent with low concentrations of nitrogen (30-70 mgN/L) and phosphorus (5-12 mgP/L), the large flows of generated wastewater carry significant quantities of nutrients. Constructed wetlands (CW) are the most common extensive NBS for nutrient recovery. They offer effective, reliable, robust and low-cost treatment of wastewater. Moreover, the nutrient content in the outflow can be adapted to the needs for crop fertigation. They can be integrated with other engineered solutions, such as anaerobic processes to meet strict water reuse regulations.

The EU-funded *HYDROUSA* project (Table 1) combines upflow anaerobic sludge blanket (UASB) with vertical constructed wetlands and UV disinfection to treat domestic sewage. The treated effluent is rich in nutrients, but has very low COD and TSS levels, and is free of pathogens. The demonstration site uses it to develop an agroforestry unit on the arid island of Lesvos, Greece, thereby reusing nutrients directly for agricultural purposes. The *HOUSEFUL* project (Table 1) also utilises domestic wastewater directly on site. It diverts the solids and liquids of the unsegregated household wastewater and treats the liquid fraction in green walls, hygenises it with UV radiation and reuses it for flushing toilets and irrigating food crops, in greenhouses. The solids are co-digested together with the organic household waste in small biogas plants. The digested matter are converted to compost into a closed-vessel composting unit with in-built odour abatement (Bertino et al. 2018).

Numerous lab-scale experiments have been conducted introducing electrodes to (constructed) wetlands (e.g. iMETland or plant-e projects), generating electricity from the oxidation of the organic matter, but only a few pilot facilities have been attempted. The *URBAN GreenUP* project (Table 1) is piloting horizontal sub-surface flow (HSSF) wetlands, where electrodes and electrical connections through the filter bed stimulate the growth of an exoelectrogenic biofilm able to transfer the electrons generated by decomposition of organic matter. The *MIDES* project (Table 1) combines urban wastewater treatment and desalination by using microbial desalination processes to generate energy and run conventional reverse osmosis with the generated electricity.

The evapotranspirative willow system (EWS) (GreenT, see Table 1) treats wastewater and produces wood biomass. Mechanically pre-treated municipal wastewater flows into a waterproof bed filled with soil and planted with selected willow clones. In two research projects funded by Slovenian Research Agency willows in this system have been found to produce significantly more biomass compared to control trees, namely 34-38 t DM/ha (Istenič et al. 2017; 2018). The treatment of wastewater produced by one person in sub-Mediterranean climate requires 42 m^2 of EWS and produces 140-179 kg of wood biomass per year. Where available space allows the application of EWS, the wood biomass produced can be used for house heating.

Microbial biotechnology

Anaerobic digestion is a popular treatment method for wastewater treatment sludge and enables recovery of energy (biogas, electricity, heat) and nutrients. Significant research is being conducted to enhance biogas and energy yields as well as valorisation of value-added products from side streams (intermediate products and valorisation of digesatate). Among the projects mentioned in Table 1, *HYDROUSA, HOUSEFUL, SMART-Plant, Pioneer-STP* and *Hamburg Water Cycle/Jenfelder Au* are applying biomethane production using technologies such as common anaerobic digester, upflow anaerobic sludge blanket, anaerobic membrane bioreactor, anaerobic biofilter. Recently, biological production and harvesting of N_2O gas for energy recovery and reduction of high nitrogen loads in digestate centrate was performed by Coupled Aerobic-anoxic Nitrous Decomposition Operation (CANDO). Combustion of N_2O with biogas increases energy yields and reduces the emission of the potent greenhouse gas (Weißbach et al. 2018).

Biofuel is usually produced from vegetable oils (soybean, canola, sunflower, palm and coconut oils) and animal fats, requesting large amounts of agricultural land. Urban wastewater can provide large quantities of alternative lipid feedstocks that help to meet the increasing demand for biofuel but do not compete with food production. Lipids, including oils, greases, fats and long-chain fatty acids are significant organic components of municipal wastewater, accounting for approximately 30-40% of the total COD of 120 g per PE and day, which means that about 18 kg per PE and year can be found in raw wastewater (Chipasa and Mędrzycka 2006). In the EU-funded WOW project (Table 1), lipids shall be accumulated by *Microthrix parvicella* bacteria and then processed to biofuel. The filamentous, selective lipid accumulator also has the ability to take up long-chain fatty acids, which can be used directly for the production of biofuel (Uwizeye et al. 2017).

The Nereda® process is a wastewater treatment technology, where activated sludge forms granules that have the ability to settle very fast. From these sludge granules, so-called `Alginate-like biopolymers` or 'Alginate-like exopolysaccharides (ALE/Kaumera)' as a raw material can be obtained (Van der Roest et al. 2015). Aerobic granular sludge from the Nereda® process contains about 15-25% ALE that can be recovered. This material has the ability to bind strongly with water, can thicken and can also be used as a basis for coatings. The wastewater-derived alginate could be used for manifold applications, e.g. in the medical and food industries (ibid). The neoalginate is already being recovered from granular sludge in three municipal WWTPs and one industrial plant in the Netherlands. The Zutphen WWTP produces 'Kaumera Nereda® Gum' (biopolymers), which can both retain and repel water. It is useful for a wide range of applications, e.g. in agriculture to reduce leaching of fertilisers and enhance crop nutrient uptake, and in the concrete industry as a water-repellent coating for concrete floors (Waterschap Rijn en IJssel 2018).

Purple Phototrophic Bacteria (PPB) can convert organic matter from wastewater and from the organic fraction of municipal solid waste (MSW) into high-value compounds. Within the *DEEP PURPLE* project (Table 1), a PPB photobiorefinery is developed combining biomass, cellulose and biogas production in one single site. PPB uses near-infrared light as the main energy source, so they do not compete with other phototrophs such as microalgae or cyanobacteria (Madigan and Jung 2009).

Polyhydroxy-alkanoates (PHAs) are bio-based and biodegradable thermoplastic polyesters. They are produced mostly from sugars or fats with pure culture fermentation. The *Phario* project (Table 1) is piloting a different approach, where secondary sludge from a municipal sewage treatment plant provides the functional biomass to produce PHA. Organic residues from the surrounding region were collected, fermented and successively fed to the sludge to produce a PHA-rich biomass with PHA content of 40-50% of the total volatile suspended solids (VSS). This PHA-rich biomass was acidified, dewatered by centrifugation and dried in a thermal dryer. The facility uses solvents such as butanol, which are reused (Bengtsson et al. 2017). The preliminary investigation was conducted in a pilot-scale facility in Brussels, using the full-scale secondary activated sludge from Bath WWTP (500,000 PE). The pilot has produced a biomass with PHA content of up to 0.47 g PHA / g VSS, which is above the considered profitability threshold (0.40 g PHA / g VSS) (ibid). Each year, 2,000-2,500 t PHA can be produced from 2,500 t VSS of waste activated sludge generated in Bath WWTP. The results showed that the harvested activated sludge could consistently yield PHA with high and controllable quality with fewer process elements, lower manufacturing costs and significantly lower environmental impact compared to currently available bioplastics.

Barriers

Reclaimed water and its treatment products can pose environmental, health and safety risks, which must be addressed during the development of resource recovery and water reuse systems. The products may contain pollutants and micropollutants like heavy metals, pharmaceuticals, personal care products, industrial chemicals, pesticides, microplastics, etc., which may enter the food chain through application to agricultural land. NBS can remove micropollutants often more effectively than conventional WWTPs (Guenther et al. 2002; Kabir, Rahman, and Rahman 2015; Balabanič et al. 2017; Gattringer et al. 2016), as conventional WWTPs are not designed to remove them. Due to their potential estrogenic, mutagenic and carcinogenic activity (World Health Organization 2011), their removal and fate in NBS is of interest for the purpose of wastewater reuse and reclamation of other derived products.

An often cited key barrier to the adoption of extensive technologies in densely populated areas (CW, algae systems and EWS) is the surface area requirement. However, microbial fuel cell technologies, active/passive aeration and innovative structural set ups (e.g. VertECO®, (Zraunig et al. 2019)) are already making CWs applicable even to cities. Furthermore, unutilised and underutilised urban spaces (incl. rooftops, façades, indoor spaces) could be used for nature-based urban wastewater treatment, resource reclamation and additional benefits, such as biodiversity, climate change mitigation and aesthetic/regenerative effects for the population. In order to facilitate the uptake of innovative rooftop and façade solutions, more demonstration projects are needed, to prove their functionality at relevant scales and a higher variety of contexts.

For research and non-research installations, the lack of standards, existing legal frameworks and lack of awareness of public administrative bodies are making it very difficult to obtain building permits for these non-conventional systems. Authorities tend to stick to existing laws and paragraphs even for research purposes, as existing legal frameworks mostly do not include an exception paragraph for research. In the Netherlands, the so-called Green Deals create a testing room for innovations for a certain timeframe (Rijksdienst voor Ondernemend Nederland 2019).

Further, the high number of different end products that can be derived can result in competition between them, e.g. if lipids are extracted for biofuel production, the potential for biogas production is reduced. Practitioners and public entities often lack the know-how to identify the optimal biorefinery design and choice of secondary products in their individual cases. This calls for increased knowledge sharing for the available possibilities and selection parameters, including technical factors as well as economic factors (supply, demand, production costs, prices). Finally, some of the mentioned technologies have yet to mature in terms of technical readiness, the enabling legal and market framework, production costs and value chain as well as comprehensive impact assessments before they can be widely applied.

4.2.2. Industrial waste and industrial wastewater

Several raw and intermediate materials can be recovered from industrial waste streams using NBS. Studies at various scales exist for the recovery of energy, carbon, nutrients, metals, and chemicals from wastewater of pharmaceutical, chemical, food processing and metal industries (Diaz-Elsayed et al. 2019; Mansouri et al. 2017; O'Dwyer et al. 2018; Song et al. 2018). Table 2 below gives an overview of recent and ongoing research projects recovering secondary resources and products from waste incineration as well as metal, dairy, food and pulp and paper industrial plants in cities.

Technologies and products

Phytomining

Phytomining is a "green" alternative to opencast mining practices (Chaney et al. 2007) often causing environmental pollution. It is applied to recover a range of metals (Ni, Co, Au) but most often is used for Ni production in abandoned ferronickel mining sites (Osmani and Bani 2017; Marilda Osmani et al. 2018; M. Osmani, Bani, and Hoxha 2018) and in naturally metalliferous soils (Li et al. 2003; Aida Bani et al. 2015; Bani et al. 2018) because this raw material has gained high economic importance. The Ni-agromining chain consists of two stages: (1) the cultivation of hyperaccumulator plants to obtain sufficient aerial biomass with a high Ni concentration, and (2) the transformation of the biomass to obtain valuable end-products. Both *in-situ* and *ex-situ* experiments were carried out in Albania, Spain, Austria, and Greece and Ni has been successfully recovered from bio-ores in pure form, as a mineral salt (ammonium nickel sulphate hexahydrate), or as eco-catalysts (Simonnot et al. 2018).

Using phytomining technology, the resulting ash is a real bio-ore, containing up to 20 weight percentages of Ni. It is possible to obtain different Ni compounds (e.g. Ni metal, Ni-based catalysts, Ni salts as ammonium nickel sulphate hexahydrate or oxides) by hydrometallurgical processes, where washing and refining processes are involved (Zhang et al. 2016, Houzelot et al. 2017, 2018). The cost of Ni is determined by the cost of the subsequent pyro-or hydro-metallurgical processes. The production of Ni compounds such as ammonium nickel sulphate hexahydrate is a better alternative for Ni metal production, because of the higher price (97.50 EUR for 500 g with 98% purity, and 134 EUR for 25 g with 99.999% purity (Sigma-Aldrich 2018)).

Constructed wetlands

The food industry produces highly nutrient-rich solid waste and wastewater, which is a large untapped nutrient source. The *HIGHWET* project (Table 2) demonstrated constructed wetlands with reduced area successfully treating wastewater from food processing plants in Spain, Denmark and Belgium. The biomass can be processed to products mentioned above (section 2.1).

Table 2. Overview of recoverable resources from industrial waste and wastewater streams in cities, by secondary resource stream, recoverable resource, technologies applied, products, scale, TRL, region and project.

Secondary resource stream	Recoverable resource	Technologies applied	Products	Scale	TRL	Region	Project	Project period	Reference
Bottom ash from incinerated MSW	Metals	Bioleaching	Enriched solution, Ga, Co, Mg, Cu, Zn, Al, Cr	micro	3-4	Austria	GrecoMet	2016-2019	https://www.alchemia-nova.net/projects/grecomet/
Metal industry contaminated soil		Agromining	Nickel salt	meso	6	Mediterranean climate	Life AgroMine	2016-2020	https://life-agromine.com/en/homepage/
Metal industry WW	Selenium, nanoparticles	Bioremediation coupled with resource recovery	Selenium nanoparticles	micro	3-4	Temperate climate	Selenex	2018-2021	http://ddg.biol.uw.edu.pl/projects/staicu-sonata/
	Metals	Microbial fuel cell	Copper	micro	3-4	Netherlands, UK, Sweden,Finland, Spain, Luxembourg	BioElectroMET	2012-2016	http://www.bioelectromet.eu/
Dairy industry WW	Carbohydrates	Fermenter-Bioaugmentation	VFAs	micro	3-4	Sweden	EnVFAPro	2017-2018	https://www.kth.se/sv/ket/resource-recovery/envfapro-1.703273
	Energy	Anaerobic digestion	Methane	micro	3-4	Denmark	ABWET	2015-2018	http://www.internationaldoctorate.unicas.it/abwet/
Food industry	Wastewater	Constructed wetland	Nutrient-rich biomass, clean water	micro	5	Spain, Denmark, Belgium	HIGHWET	2013-2015	http://www.highwet.eu/
Pulp industry craft mill foul condensate	Organic carbon	Acetogenesis (anaerobic digestion)	VFAs	micro	3-4	Italy	ABWET	2015-2018	http://www.internationaldoctorate.unicas.it/abwet/
Pulp and paper industry WW	Carbohydrates	Dark fermentation	Hydrogen, VFAs	micro	3-4	Italy	ABWET	2015-2018	http://www.internationaldoctorate.unicas.it/abwet/

ABWET: Advanced Biological Waste-To-Energy Technologies
EnVFAPro: Enhancement of Volatile Fatty Acid Production From Dairy Wastewater
HIGHWET: Performance and validation of HIGH-rate constructed WETlands
GrecoMet: Green Recovery of Metals

Selenex: Harvesting resources from industrial streams

Se is an essential micronutrient and a critical raw material with wide-range industrial utilisation (Hennebel et al. 2015). The current production of Se involves energy-intensive pyrometallurgical processing and smelting of Cu and Pb-ores, where it is recovered as an impurity. As a solution to its scarcity, Se could be recovered from industrial, secondary resources, such as effluents of Flue Gas Desulfurisation (FGD), using cost-effective and environmental-friendly biotechnological approaches (Cordoba and Staicu 2018). Various bacterial groups can metabolise Se to generate cellular energy (i.e. ATP) through anaerobic respiration, in parallel with the production of solid Se nanoparticles (Ni et al. 2015), as displayed in Figure 2.

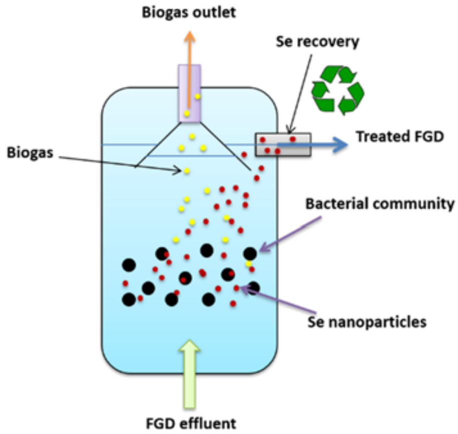

Figure 2: Biological treatment and recovery of selenium using a biotechnological approach (modified from Cordoba and Staicu, 2018).

Copper recovery from metallurgical waste and process streams using microbial fuel cells (MFCs) has been demonstrated. In MFCs, bacteria act as biocatalysts at the anode and generate current by oxidation of organic or inorganic substrates. The current can be used at the cathode to reduce e.g. metal ions to solid metal species. Biological oxidation of either acetate (Rodenas Motos et al. 2015) or tetrathionate (Sulonen et al. 2018) has been coupled to Cu recovery in lab-scale MFCs. Furthermore, an MFC coupling acetate oxidation to Cu recovery was scaled-up to bio-anode and cathode surface areas of 835 cm^2 and 700 cm^2, respectively (Rodenas Motos et al. 2017).

The dairy industry wastewater contains high amounts of biodegradable carbon (Slavov 2017) and is a great source for the production of volatile fatty acids (VFA), which are valuable intermediate products of anaerobic digestion used in the conventional chemical industry. VFA on the market include formic, acetic, propionic, butyric, valeric and caproic acid. VFA have a wide range of applications, their recovery generates high production yield and releases less GHG emissions than biogas production (Atasoy et al. 2018). Bioaugmentation of the mixed cultures with pure *Clostridium aceticum* cultures has proven to increase acetic acid production by 96 times, bioaugmentation with *C. butyricum* increased butyric acid production 120 times and *Propionibacterium acidipropionici* increased propionic acid production around 5 times compared to the control experiments. This case study (EnVFAPro project, Table 2) has shown that bio-based VFA production from waste streams can be environmentally friendly and economically feasible.

A pilot study (*HIGHWET* project, Table 2) at industrial food processing plants in Spain and Denmark tested the effect of effluent recirculation, aeration regime and different phosphorus adsorbent materials in a system that combines a hydrolytic up-flow sludge bed (HUSB) anaerobic digester as primary treatment, hybrid (vertical and horizontal flow (VF-HF)) constructed wetlands (CWs) and two different phosphorus adsorbent materials for treatment of the wastewater characterised by high nutrient loads. The project achieved to decrease the required surface of conventional HFCWs and improved the final effluent quality in the aerated and non-aerated line, but the aerated VFCW was able to treat a four times higher loading rate with similar treatment efficiency than the non-aerated VFCW (Pascual et al. 2018).

Dairy wastewaters contain lipids that are hydrolysed into long-chain fatty acids (LCFA) that may be inhibitory to anaerobic microorganisms. Anaerobic conversion of LCFAs to methane was reported for the first time at 10°C and 20°C (with lipid content of >1%) in batch bottles, where the role of aceto-clastic methanogens from the genus *Methanosaeta* was highlighted (Singh et al. 2019). In pulp industry, recovery of chemicals from black liquor results in the production of condensates that contain methanol up to 46 g/L. The pulp industry also produces thermomechanical pulping wastewaters that are released at high temperatures (50-80°C). Conversion of methanol from condensates to VFA has been reported with an acetogenic culture in an up-flow anaerobic sludge bed reactor (Eregowda et al. 2018). Thermomechanical pulping wastewater, on the other hand, has been anaerobically converted to hydrogen at 70°C with a culture dominated by *Thermoanaerobacterium* sp. (Dessì et al. 2018).

A variety of products can be recovered using microbial technologies, depending on the type of waste stream and desired recovered product, including metals (Wang, Xu, and Sheng 2019), nanoparticles (Goethem et al. 2018), VFA (Zacharof and Lovitt 2014) and renewable energy carriers such as biogas and biofuel. Among a wide variety of recovered products from industrial waste streams, the described products are most promising with their potential as a raw material for post-processing. Most of the described technologies are still being developed at laboratory and/or pilot scales (e.g. bio-electrochemical systems, VFA production) (Chen et al. 2017; Jankowska et al. 2017; Garcia-Aguirre et al. 2017), except biogas production, which is established and implemented at full scale (Mauky et al. 2017; Martí-Herrero et al. 2019). In addition to biogas, bioplastic production has also been applied at pilot-scale (Tamis et al. 2018). Mo, Man, and Wong (2018) used food waste, fish waste, and food processing waste to produce fish feed through biotransformation and solid-state fermentation.

Barriers

The phytomining techno-economic model should be customised to country-specific data reflecting differences in soil physicochemical properties in relation to the phytomining system implemented, Ni concentrations in the soils, hyperaccumulator yields and metal prices. The process efficiency and Ni salt purity are the main challenges of phytomining. The process parameters such as stirring speed or reaction time can significantly influence efficiency and they should be thoroughly investigated to assess their influence at each step of phytomining. One of the main limitations of energy recovery is the temperature of combustion. Previous experiments demonstrate that combining energy recovery and utilisation of ashes for Ni recovery are compatible if the combustion temperature is low enough to avoid Ni losses through fly ash or other outputs. Preliminary calculations for Ni phytomining show promising results under the condition that heat released during incineration can be valorised close to the processing facility.

The main limitations are related to the complex matrix of industrial effluents, which often contain toxicants, which limit or prohibit bacterial growth. To overcome these hurdles, the recovery systems need to employ mixed microbial communities (as opposed to pure bacterial cultures). These mixed communities offer the advantage of protecting the microbial species of interest (e.g. metal respires or methanogens) against the toxic environment of the industrial effluent. But on the other side, mixed communities also result in competition between various bacterial groups, some having better fitness and thermodynamics than the ones of interest for resource recovery (e.g. more thermodynamically adapted sulphate-reducing bacteria vs. methanogens or metal oxidisers) (Tang et al. 2019; Cetecioglu et al. 2019; Hoelzle, Virdis, and Batstone 2014).

Another major challenge is the large variation in the composition and/or volume of the wastewaters, which may result from varying feed material composition, periodic operation or production intermissions due to e.g. maintenance and cleaning. In addition, although it is a promising approach to recover bio-based products from industrial and municipal wastewater, there are still some technical challenges such as product recovery after anaerobic digestion and purity of the recovered products (Atasoy et al. 2018; Puyol et al. 2017). Therefore, the microbial technologies should be able to cope with these changes, where mixed microbial communities again are more resilient than pure cultures. To reach full-scale adaptation, the microbial technologies should thus be able to handle high organic loading rates, regarding also high nitrogen and phosphorous concentrations and ensure sufficient wastewater treatment and resource recovery/product spectrum at varying wastewater conditions. By scaling up these systems, broad communication with stakeholders is crucial for preparing the market with new bio-products such as VFA.

Finally, many of the technologies that enable recovery of products other than energy are still in development and applied so far only at lab and pilot scales. The next step for these technologies will be scale-up to demo and flagship scales. However, already at this stage, the communication with public and private stakeholders is essential to prepare the market including legislative and regulatory framework for the new bio-products.

4.2.3. Municipal solid waste

According to the European Commission (2019), municipal solid waste (MSW) constitutes about 10% of total waste generated in the EU. Although this figure may not seem too excessive at first glance, MSW is extensively prevalent and requires complex management linked to the mixed composition and multiple points of collection, which require various treatment methods. MSW includes waste streams from households and similar wastes from commerce, offices, public institutions and selected municipal services, excluding municipal sewage and construction and demolition waste (CDW). NBS applied to recover a wide range of intermediate and final products from mixed or biodegradable MSW include composting, anaerobic digestion and Mechanical Biological Treatment (MBT). Research has also been conducted on bioleaching from mixed MSW incineration ash. Table 3 below gives an overview of recent and ongoing research projects recovering secondary resources and products from MSW streams

Technologies and products

Resource recovery from mixed MSW

Mechanical Biological Treatment (MBT) can enable recovery of ferrous metal, non-ferrous metal, plastic and glass from mixed MSW, but is mainly applied to stabilise MSW before landfilling. The biological steps include anaerobic digestion, composting and biodrying. Where recycling and recovery activities are low, it can improve environmental and economic performance (Trulli et al. 2018). But MBT achieves only lower quality recyclates compared to those derived from recyclables from separate household collection, and mostly only metals are extracted. Digestate derived from mixed MSW is generally reported to be of lower quality than from separately collected organic waste, largely due to contamination with e.g. glass and potentially toxic elements such as heavy metals (EPEM S.A. 2011). Biodrying is a partial composting stage, where the action of aerobic microbes rapidly heats and dries the waste. This process is used to produce a refuse-derived fuel that is dry and light for transport (Bogner et al. 2007).

Table 3. Overview of resources that can be recovered from different MSW streams, recovery technologies applied, recovered products, scale, TRL, region and project information.

Secondary resource stream	Recoverable resource	Technologies applied	Products	Scale	TRL	Region	Project	Project period	Reference
Biodegradable fraction of MSW	Energy, nutrients	Separate collection at city level, centralised AD (digestion) and composting	Biogas, electricity and thermal heat, compost	macro	8	Ljubljana, Slovenia	Centralised AT and composting at city level, e.g. RCERO	2007-2015	http://www.rcero-ljubljana.eu/upload/dokumenti/rcero_ljubljana_brusura_ang.pdf
		Separate collection at city level, centralised AD (digestion)	Methane for transportation, digestate (fertiliser)	macro	8	Reykjavik, Iceland	Centralised methane recovery at city level CIRCLENERGY	2017-2018	https://www.carbonrecycling.is/circlenergy
	Nutrients, lipids, cellulose	Microbial conversion of nutrients to high-value compounds in a biorefinery approach	Ectoine, PHA, biogas, cellulose, construction materials	meso-macro	6	Spain	DEEP PURPLE	2019-2023	https://deep-purple.eu/
	Organic carbon, energy, nutrients	Closed vessel composting system with integrated plant biofilter	Biomass, odour removal, oxygen	micro, meso	6	Austria, Greece, Spain	HYDROUSA, HOUSEFUL	2018-2022	https://www.alchemia-nova.net/projects/houseful/
Food waste and primary sludge	Carbohydrates	Acetogenesis (anaerobic digestion)	VFAs	micro	3-4	Sweden	CarbonNextGen	2018-2020	https://resource-sip.se/projects/nasta-generations-koldioxidneutrala-avloppsreningsverk-carbonnextgen/
Food and garden waste + construction & demolition waste (CDW)	Green waste compost + crushed CDW material	Green waste compost and CDW are mixed 50:50	Improved soil-like substrate	micro, meso	6	Scotland	The James Hutton Institute	2019-2021	https://www.hutton.ac.uk/staff/luke-beesley

DEEP Purple: Conversion of diluted mixed urban bio-wastes into sustainable materials and products in flexible purplephotobiorefineries
HOUSEFUL: Innovative circular solutions and services for new business opportunities in the EU housing sector
HYDROUSA: Demonstration of water loops with innovative regenerative business models for the Mediterranean region
RCERO: Regional Waste Management Center of Ljubliana

Mixed (residual) MSW is often incinerated for electricity and heat production, and the incineration ash landfilled. The GRecoMet project (Table 3) (alchemia-nova 2019b) applied *Acidithiobacillus* bacteria (among other trials) to recover metals (finally selecting Cu, Cd and partially Co) from MSW incineration ash. The diffusely dispersed metals are brought into solution through microbial leaching, a process that efficiently extracts metals even from low-grade ores, such as MSW incineration ash (Chemiereport.at 2017). In next steps, for enrichment of the dissolved metals, different NBS were tested, namely enrichment in living and dead microalgae, rhizofiltration and sorption through peptides from microbial cells and waste biomass (biosorption). Hemp shives and sugar beet residues showed the highest sorption rates. Recovery of the pure metals from the metal-enriched biomass was achieved through hydro- and pyrometallurgical pathways. The results suggested hydrometallurgical recovery directly from the leachate to be the most feasible option.

Resource recovery from the biodegradable fraction

If biodegradable municipal waste (garden and food waste from households, restaurants, supermarkets) is separated from other MSW at the source, it can be used as a carbon and nutrient source to produce several safe (uncontaminated) and valuable bio-based products (Atasoy et al. 2018). With 88 million tonnes of food waste produced in the EU every year (Kibler et al. 2018), this represents a waste stream with great potential for resource recovery. Composting and anaerobic digestion are commonly used processes.

Besides applying green waste compost (GWC) directly to fields and green spaces, it can also be mixed with deconstruction materials (CDW) to create a functional soil-like substrate (Table 3, *The James Hutton Institute*)). CDW and GWC represent the mineral and organic parts of soil, respectively. In experiments growing ryegrass *Lolium perenne* and reed canary grass *Phalaris arundinacea,* a 50:50 volumetric ratio substrate yielded significantly greater biomass than other mixing ratios, and greater than that of the control soil (local topsoil). Such 'technical' soils and substrates can be produced from a range of urban wastes and, after physical, biological and chemical testing and verification, are envisaged as possible replacements to degraded or sealed soils in urban environments, creating bulk soils for the restoration of old capped landfill and mine site areas, and as alternative substrates for the growth of bioenergy crops (Nehls et al. 2015). Monitoring of leachates from such created substrates is required as materials such as CDW can contain high quantities of problematic components such as gypsum, for example, which results in sulphate leaching.

Biomethane production and further heat and electricity production are common resource recovery technologies for kitchen waste (biodegradable fraction of MSW). Co-digestion of food waste with other waste, such as municipal wastewater (sludge) has been found to achieve a substantial increase of energy generation. Estimates of methane yields from various substrates can be found in Methane Yield Database: online infrastructure and bioresource for methane yield data and related metadata (Murovec, Kolbl, and Stres 2015)[1]. The digestate is used as crop fertiliser (or soil conditioner), for microalgae cultivation, and in other cases further processed for biofuel and bioethanol production. As mentioned in section 2.2, VFA are valuable intermediate products of anaerobic digestion. VFAs gained from food waste have also been processed to substrate for the production of biofuels, such as methane, hydrogen (e.g. Saadiah et al. 2017), and biofuel (Wang, Xu, and Sheng 2019) as well as biopolymers such as polyhydroxyalkanoates (PHAs) (Raganati et al. 2014; Domingos et al. 2017). Physical, chemical and biological pre-treatment (via enzymes) methods exist to improve the degradation of cellulose and hemicellulose solubilisation (Strazzera et al. 2018), sugars production and thus of VFAs (Braguglia et al. 2018). Atasoy et al. (2018) found that the organic fraction of MSW

[1] The database is freely accessible on the web page http://methane.fe.uni-lj.si/.

achieved the highest acidification and therefore highest yields after cheese whey and molasses (up to 40%).

Barriers

While composting and anaerobic digestion are well-established processes at mesoscale, the decentralised microscale for biogas production requires further research and development and is often confronted with legal barriers. Further, research to optimise anaerobic digestion is focused on improving biogas yield, while neglecting the quality of digestate (Logan and Visvanathan 2019). Logan and Visvanathan (ibid) call for a shift from 'biogas optimisation' to 'integrated biogas-digestate optimisation'. Such an approach would consider potential value addition from digestate, which is generally not commercially exploited. Value addition with products for high-value markets is still in its infancy, with most attempts currently limited to lab or pilot scale.

4.2.4. Gaseous effluents

NBS can remove, contain and degrade gaseous contaminants into non-toxic or less toxic substances. These processes use the natural ability of plants to metabolise nutrients. They can also be enhanced by microbial and fungal communities colonising plant roots and above-ground organs of plants (e.g. Wood et al. 2006; Xu, Wang, and Hou 2011). Together, they can purify indoor and outdoor air from common pollutants including PMs (particulate matter), SO_2, NO_x, N_2O, O_3, VOCs (volatile organic compounds) (Wei et al. 2017), while also utilising CO_2 as a building block for plant biomass and releasing O_2. In doing so, these living biofilters can be used to transform polluted air into clean air and simultaneously produce plant biomass which can be processed into a range of secondary materials.

However, while terrestrial plants provide their aesthetic value and other co-benefits, the pollutant conversion and photosynthetic efficiency of microalgae are much higher. Microalgae (photosynthetic microorganisms, here including prokaryotic cyanobacteria and eukaryotes) can convert 10-20% of average solar energy in a mid-latitude region to biomass energy, versus 0.5% for the fastest-growing terrestrial plant, switchgrass (Li et al. 2008). Besides their high growth rate, microalgae can tolerate high CO_2 concentrations in gas streams; e.g. *Spirulina sp., Scenedesmus obliquus* and *Chlorella vulgaris* grow with up to 18% CO_2 (Morais and Costa 2007), allowing for high conversion efficiencies and enabling greater biomass harvests for further processing to biofuels including biogas, biooil, biohydrogen (Li et al. 2008). In addition to biofuel, which is a low-value, high-volume product, a number of high-value chemicals can be derived from microalgae and are already widely marketed, such as omega fatty acids and astaxanthin (Borowitzka 2013). The commercial cultivation of microalgae has rapidly increased over the last decades (Plaza et al. 2009).

NBS applied for resource recovery from gaseous effluents essentially include technologies using plants, plant-surrounding microorganisms as well as microalgae photobioreactors (PBRs) to store CO_2 and produce oxygen and biomass for further uses. These technologies are designed to purify ambient air, or by injecting gas directly into systems such as algae panels or tubes, or green walls. Table 4 below gives an overview of recent and ongoing research projects recovering secondary resources and products from gaseous effluent streams in cities.

Table 4. Overview of resources that can be recovered from different gaseous effluent streams found in cities, recovery technologies applied, recovered products, scale, TRL, region and project.

Secondary resource stream	Recoverable resource	Technologies applied	Products	Scale	TRL	Region	Project	Project period	Reference
Vehicle exhaust gases, road traffic	CO_2-C, clean air	Glass tubular photobioreactors using algae	Combustible biomass, oxygen	micro	7	Geneva, Switzerland	Culture Urbaine	2014	https://urbannext.net/culture-urbaine/
Outdoor air in urban spaces	Clean air	Plant-based green wall	Filtered air	micro	5	EU	Green INSTRUCT	2016-2020	https://www.greeninstruct.eu/
		Large-scale green wall facade	Filtered air	micro	8	Austria	Grünwand	2009-2013	https://gruenwand.com/
	CO_2-C, clean air	Mobile pods with tubular algae PBR structures	Oxygen, canopy area	micro	3	Hungary	Chlorella Oxygen Pavilion	2012	(Miklosi 2013)
		Curtain style vertically positioned algae reactor	Bioplastics, oxygen	micro	6	United Kingdom	photo.Synthetica EcoLogicStudio	since 2018	https://www.photosynthetica.co.uk/
		Open algae tanks	Animal feed (protein), filtered air	meso	7	Bangkok, Thailand	EnerGaia	since 2009	https://energaia.com/
		Bio-wall type moss system	Filtered air	micro	6	Germany	CityTree	since 2015	https://greencitysolutions.de/en/
	CO_2-C, energy, clean air	Flat-panel photobioreactors (PBRs) using algae	Heat, biogas, oxygen	micro	7	Hamburg, Germany	Building with Bio-Intelligent Quotient (BIQ)	2011-2013	https://www.buildup.eu/en/practices/cases/biq-house-first-algae-powered-building-world
		Wastewater treatment by open raceway algae ponds, anaerobic digestion, digestate dewatering, lipid extraction, biogas upgrading	Biofuel, biofertiliser, biomethane	macro	6	El Torno Chiclana, Spain	All-Gas	2011-2016	http://www.all-gas.eu/en/
Industrial flue gas	CO_2-C, clean air	Vertically positioned plastic disks generating algae	Dry biomass, oxygen	meso	5	Spain	ALGADISK	2012-2014	https://algen.eu/node/153

		biofilms; continuous harvesting							
	CO_2-C, energy, clean air	Photobioreactor and photofermentation, anaerobic digestion of cyanobacteria residue	Bioplastic (polyhydroxybutric acid, PHB), biogas, nutrients for bacteria cultivation, fertiliser	meso	6-7	Austria	CO_2USE	2012-2015	https://www.energy-innovation-austria.at/article/co2use-2/?lang=en
Indoor air	Clean air	Active hydroculture plant-based air treatment chambers	Filtered and humidified air	micro	6	Denmark, UK, Switzerland, Spain	RECO_2ST	2018-2022	https://reco2st.eu/
Indoor air (households and other buildings), or flue gas from biogas CHP	CO_2-C, energy, clean air	Wall décor type algae biofilms; combination with biogas Combined Heat Power	Filtered air, biogas, electricity, heat	micro	7	Germany	SOLAGA	Since 2015	https://www.solaga.de

ALGADISK: Novel algae-based solution for CO_2 capture and biomass production

Green INSTRUCT: Green INtegrated STRUCTural elements for retrofitting and new construction of buildings
ReCO2ST: Residential Retrofit assessment platform and demonstrations for near zero energy and CO2 emissions with optimum cost, health, comfort and environmental quality

SOLAGA: Living wall elements with algae

Technologies and products

The origin of plant-based air treatment falls back to the 1980s, where Wolverton et al. developed the first systems for NASA (Wolverton and McDonald 1983; Wolverton and McDonald-McCaleb 1986; Wolverton and Wolverton 1993). Within the last years, several plant-based air treatment systems have been developed at meso-scale, like Cloud Garden in the Netherlands (Cloud Garden 2019) and Green City Solutions in Germany (Green City Solutions 2019).

Green walls and microalgae structures are the most popular applications, usually applied with the foremost objective to purify ambient air in cities, i.e. bioremediation of indoor or outdoor air, binding or degrading various air pollutants. Especially, indoor air purification can have significant human health benefits as people in industrialised countries spend approximately 22 hours per day indoors. Air pollutants, which are generated indoors, e.g. VOCs, often accumulate due to limited ventilation (Pettit et al. 2018). Amid global warming, technologies such as active green walls, i.e. with active aeration, will gain importance due to their co-benefits of reducing indoor temperatures by 4-6 degrees Celsius if close to an indoor wall (Fernandez-Cañero et al. 2012).

Outdoor structures with public visibility are typically designed to enhance the aesthetic value of urban spaces, such as green walls and the microalgae structures installed by EcoLogicStudio in the UK and other European countries. Green walls have been set up at all scales, from small indoor units to outdoor multi-story façades, e.g. by Grünwand (Techmetall 2019) and the famous 'vertical forest', a high-rise apartment building in Milan designed by the architect Stefano Boeri, featuring 20,000 plants, 800 trees, and over 100 different species. The vertical forest absorbs 40 tonnes of CO_2 and 1.5 tonnes of fine PM each year, generating 90 tonnes of oxygen per year (Bezemer 2017).

As listed above (**Fehler! Verweisquelle konnte nicht gefunden werden.**), NBS can be used to derive a number of products from gaseous effluents. Plant-based technologies filter the air and convert CO_2 to biomass and O_2, producing opportunities for biomass processing to various mentioned products, while also improving ambient air quality. Low-value, high-volume products are mentioned in section 2.1. High-value chemicals derived from microalgae include β-carotene, astaxanthin, docosahexaenoic acid, eicosahexaenoic acid, phycobilin pigments and algal extracts for use in cosmetics as well as polyunsaturated fatty acids, widespread 'superfoods' *Chlorella* and *Spirulina* (Borowitzka 2013), bioactive medicinal products, antioxidants, colouring agents and vitamins (Khan et al. 2018). Aromatic essential oils can be derived from plants used for phytoremediation. Processes such as steam distillation ensure that the oils are free from unwanted contaminants including heavy metals (Pandey and Souza-Alonso 2019). The following section describes case studies at micro, meso and macro level.

Micro

RECO₂ST (Table 4) is an EU-funded building renovation project aimed to achieve major energy savings through optimised refurbishment and integrated installation tools, including NBS, specifically, two biotechnical air treatment systems for purification, cooling and humidification of indoor air. The first is a mobile pot plant-based unit either as part of a retrofit or as a standalone unit. In the second system, ambient indoor air is treated by directing ventilation through a "wintergarden"-like plant chamber. Both systems are hydroculture, with active aeration and automated sensors measuring air quality parameters. They can reduce PMs, VOCs, achieve stable indoor temperatures, rehydrate the air and enrich building aesthetics. As a result, overall quality of life, human health, and productivity of building inhabitants will be significantly improved. Current demo sites include apartment blocks in Frederikshavn (Denmark), London (UK), Vevey (Switzerland), and Cadiz (Spain). The ideal application is in office buildings, which are densely populated for many hours a day.

Meso

The *BIQ-building* (Table 4) in Hamburg, Germany, is the first algae-powered building in the world (IBA Hamburg GmbH 2013). Microalgae are bred in the glass façades, providing sufficient biomass to cover electricity and heat requirements of the whole building. Completed in 2013, *BIQ* is a five-story, 15-apartment passive house designed by the Austrian architectural firm Splitter-Werk and funded by the Hamburg-based Climate Concept Foundation. The building features two types of photobioreactor (PBR) façades, where algae are grown for energy production as well as for controlling light and shade. The PBRs are filled with microalgae culture medium and supplemented with CO_2. Flue gas from a biogas-fuelled micro-CHP (combined heat and power) unit is injected into the PBRs. Circulated culture medium is collected at a central location within the building where recovered heat is drawn off by a heat exchanger and collected algal biomass is shipped to an off-site biogas unit. For infrastructural and legal reasons, biogas is not generated within the building. The PBR façades of *BIQ* generate 15g total solids (TS) per m^2 per day across $200m^2$ (300-day indicator), yielding 2,600 m^3 methane and 6,000 kWh of net energy equivalent per day.

In the *CO_2USE* project (Table 4), cyanobacteria convert off-gas from an industrial production plant to biomass, which is further processed to bioplastic (PHB) as well as to biogas and digestate. The digestate is used to provide nutrients for bacteria cultivation and as common agricultural fertiliser. An ecological assessment showed that greenhouse-gas emissions from PHB production can be up to 75% lower than for conventional polypropylene (BMVIT 2017).

Macro

In the EU-funded *All-Gas* project (Table 4), microalgae are cultivated in high-rate algal ponds (HRAP) with raceway design (with closed loop recirculation channels), filled with pre-treated urban wastewater. CO_2-containing flue gas from the biogas upgrading column is injected into the ponds and converted to algal biomass and further to secondary bioproducts. An anaerobic digester converts the harvested algal biomass to biogas and digestate. Biofuel is gained through lipid extraction from dried digestate. The residue from lipid extraction is distributed as biofertiliser. The total 4 ha site located at a municipal WWTP in Chiclana, Spain, generates around 400 tonnes of biomass per year.

Barriers

A challenge to comparison and further development of active botanical biofilters are the diverse experimental approaches assessing their performance, including different structural designs, different types and doses of pollutants as well as different time frames (Pettit et al. 2018).

Plant-based air purification systems are limited by their metabolic detoxifying capacity, thus requiring significant area compared to common purification systems. However, vertical structures enable greater plant density for floor space. Su and Lin (2015) found that, within an hour, a 6 m^2 indoor green wall could lower CO_2 concentrations from 2,000 to 800 ppm in a 39 m^3 room. In outdoor setups, the reduction rate is much smaller, but the aesthetic and stress-reduction potentials of greener cities argue for plant structures at larger scales. However, the maintenance required for healthy plants and their microbial populations remains a major drawback (Pettit et al. 2018). For plant systems, the use of invasive species poses a threat to sustainability and long-term feasibility (Pandey and Souza-Alonso 2019).

One side effect of plants, especially in cities are their VOC emission. In that context use of species from the gender of *Populus*, *Salix*, *Platanus,* and others might be problematic. Isoprene emission from leaves of these species in summer months can increase formation of tropospheric ozone and other secondary pollutants in air (Sharkey et al. 2008). Consequently, a selection of plants with low VOC emissions themselves for plant-filter use is of great importance.

Another limitation is the diffusion of gaseous pollutants and associated removal inefficiencies, which can be mitigated by active airflow through plant substrate, e.g. active green walls (Pettit, Irga, and Torpy 2018), or microalgae PBRs (Malinska and Zabochnicka-Swiatek 2010). On the other hand, high contaminant concentrations can inhibit plant and algae growth, i.e. their purifying activity. While microalgae growth is not limited by NO_x, SO_x concentrations above 400 ppm can lead to the formation of sulphurous acids and lower the pH. If the pH reaches below 4, the productivity of microalgae is reduced. This can be mitigated by applying NaOH to increase the pH (Malinska and Zabochnicka-Swiatek 2010). When microalgae (or plants) are harvested and processed for biofortification or fertiliser uses, careful analyses are necessary to exclude risk of contamination (Pandey and Souza-Alonso 2019). Closed PBRs overcome problems of external contamination (Malinska and Zabochnicka-Swiatek 2010). Regarding plant biofilters, it is suggested to use non-edible high-value crops for the treatment (Pandey and Souza-Alonso 2019).

Finally, a major challenge is that many secondary commercial products that can be derived from microalgae require further R&D to become profitable (Borowitzka 2013), such as PCB bioplastics (BMVIT 2017). The design of advanced PBRs, methods to enhance microalgae growth rates, the harvesting and drying methods, product synthesis and biomass pre-treatment are cited as crucial to improve cost-effectiveness of microalgae systems (Y. Li et al. 2008; Malinska and Zabochnicka-Swiatek 2010; Khan, Shin, and Kim 2018). For mass microalgae production, flat plate and raceway PBRs are economically feasible, as opposed to horizontal tubular PBRs (Malinska and Zabochnicka-Swiatek 2010). Another factor for commercialisation is the highly disparate sizes of the markets for biofuels and high-value derivates, which may change in the light of current increased efforts to commercialise and develop new microalgae products (Borowitzka 2013).

4.3. Source-separated waste

By implementing source separation solutions, domestic waste streams can be collected with higher nutrient levels and higher concentrations of organics (COD, BOD), for which clever sewage treatment and recovery technologies have been conceived. Such technologies minimise the release of toxic substances and protect natural freshwaters from eutrophication due to excess nutrient loadings (Finger et al. 2013). To obtain concentrated waste streams, dilution of solid and aqueous wastewater needs to be prevented. First of all, a separate sewer system with a sanitary and storm sewer can increase pollutant concentrations in wastewaters by around 85%, as calculated from typical German flow rates (Brombach, Weiss, and Fuchs 2005).

Secondly, several options have been proposed for source separation at the household level of either urine (yellow water (YW)), using water-free urinals or source separation (NoMix) toilets and brown water (feces), or black water (BW). The latter waste stream combines urine and feces but in the selected case studies, dilution is avoided by means of vacuum toilets requiring low amounts of flushing water, and further separated vacuum transport. Another option is waterless dry toilets with or without urine separation. The collected dry toilet matter (DTM), depending on the type of toilet, can contain feces, urine, toilet paper, and structural material. The sanitary wastewater from the laundry, kitchen, shower, and bath is referred to as greywater (GW) and is separately collected as well. Finally, organic waste produced in cities can be separated as well. We make the difference between kitchen waste (KW); bio-waste (Bio-W) referring to the combination of food waste and more general, the biodegradable fraction of catering waste; vegetable, fruit and yard waste (VFY), which is collected separately in several European cities; and green waste (GrW) collected in gardens and urban green spaces.

Coupling source separation to decentralised treatment/recovery of domestic wastewater, dry toilet matter and household waste (fractions) allows the recovery of valuable resources such as nutrients, organics, energy, and water more efficiently. Table 5 below gives an overview of recent and ongoing research projects recovering secondary resources and products from different source-separated waste and wastewater streams in cities.

Technologies and products

Micro

Sanitation 360 aims to produce fertiliser from human urine inside the toilet. The natural and fast enzymatic degradation of urea is chemically inhibited at pH 10 (Randall et al. 2016; Senecal and Vinnerås 2017; Simha et al. 2018; 2018). Thereafter, the water in the YW is evaporated and ventilated away leaving a fertiliser product with commercial-grade nutrient concentrations (>10% N, >1% P and >3% K). The decentralised inside-the-toilet approach to urine management allows large scale implementation without major changes in the infrastructure, only requiring a new toilet and a drying bed. The first pilot systems have been implemented in single urine-diverting toilets in Sweden. A similar system is implemented in the Autarky toilet developed at the Swiss Federal Institute of Aquatic Science and Technology (EAWAG) in Switzerland, where the YW is treated and used locally for fertiliser production (Larsen et al. 2015).

At the *Forum Chriesbach* office building in Duebendorf, Switzerland, a YW nutrient recovery system for 220 people has been in operation since 2012 (EAWAG 2019). YW is collected with waterless urinals and NoMix toilets and is directed to collection tanks in the basement. The urine is then nitrified in an aerated bio reactor (Etter, Udert, and Hug 2013), followed by a polishing step with activated carbon to eliminate pharmaceuticals and hormones. A vacuum distillation step reduces the liquid volume by 93% and eliminates pathogens. The product, a concentrated and processed urine-based fertiliser, contains all primary and secondary nutrients of the collected urine and is a fully approved fertiliser in Switzerland. It is produced and marketed as “Aurin” by Vuna GmbH, a spin-off company of Eawag (VUNA GmbH 2019). The main success factor was the determination of the EAWAG board to realise the new office building as a lighthouse project for integrated sustainable building practices, as well as the approval and support of the Swiss National authorities. The water and sanitation system was an important part of this broader context.

Meso

The city of Sneek, The Netherlands has two areas with source separation systems: *Lemmerweg* (since 2005) and *Noorderhoek* (since 2010). BW is collected by means of vacuum collection (toilets) and transport systems that require about seven times less water (1 L per flush) than conventional sanitation. The developed sanitation concept (Zeeman et al. 2008) was first tested for several years with 32 houses at the *Lemmerweg*, and subsequently applied for 232 households in *Noorderhoek*. The highly concentrated BW is mixed with ground KW and treated anaerobically in an Upflow Anaerobic Sludge Bed (UASB) reactor (Lettinga et al. 1981). A similar concept is now under construction for 550 houses in Amsterdam. The influent COD load is degraded, on average, for 70% resulting in a yearly biogas production of 10,5 Nm^3/IE/a (Wit et al. 2018). Biogas energy is recovered as heat and used in a district heating system. Nitrogen is removed from the UASB effluent, using oxygen-limited autotrophic nitrification/denitrification (OLAND) (Vlaeminck et al. 2009). Phosphate is recovered as struvite and locally reused as fertiliser. GW is, together with the BW effluent, aerobically treated. GW has the highest temperature and energy potential to recover, and heat recovery through heat exchangers allows to transfer most of the energy to the district heating system. A schematic representation of the applied concept is given in Figure 3.

Table 5. Overview of technologies applied to recover resources from source-separated urban waste(water), different secondary resource streams, recoverable resources, technologies applied, recovered products, scale, TRL, region and project.

Secondary resource stream	Recoverable resource	Technologies applied	Products	Scale	TRL	Region	Project	Project period	Reference
Source seperated urban WW + kitchen waste	Reclaimed water, energy & nutrients	Vacuum collection, AD, OLAND, struvite precipitation AD, heat exchange, district heating	Biogas, struvite fertiliser, thermal energy (heat)	meso	8	Sneek, Netherlands	Lemmerweg and Noorderhoek RUN4LIFE	2017-2021	http://run4life-project.eu/
		Vacuum toilets and collection, AD, struvite precipitation AD in a membrane bioreactor, RO, heat exchange, district heating	Biogas, struvite fertiliser, heat, water reuse for industry	meso	8	Ghent, Belgium	De Nieuwe Dokken RUN4LIFE	2017-2021	http://run4life-project.eu/
		Water-free urinals, vacuum toilets, AD, struvite precipitation	Biogas, struvite fertiliser, thermal energy (heat)	meso	7-8	The Hague, Netherlands	Rijkskantoor, Rijnstraat, NL	2017	https://www.saniwijzer.nl/projecten/rijkskantoor-rijnstraat-8/detail=94
Yellow water	Nutrients	Inside-the-toilet urine drying after chemical stabilisation	Dry fertiliser	micro	7	Sweden	Urine dehydration technology for sanitation 2.0 Sanitation 360	2015-2018	https://www.slu.se/en/departments/energy-technology/projects/kretslopp/productive-on-site-sanitation-system/
		Water-free urinals, NoMix toilets, nitrification, activated carbon, distillation	Concentrated liquid fertiliser "Aurin" (VUNA GmbH)	micro	8	Duebendorf, Switzerland	VUNA – Nutrient Recovery from Urine	2010-2015	https://www.eawag.ch/en/department/eng/projects/vuna/
Grey water + dry toilet matter	Nutrients, organic carbon	Constructed wetland for greywater treatment; waterless dry toilets, composting and vermicomposting	Compost	meso	8	Cressy, Geneva, Switzerland	Cooperative Equilibre @ Cressy	2011-2018	https://www.cooperative-equilibre.ch/projets/cressy/historique-de-limmeuble-de-cressy/
Grey water	Reclaimed water and nutrients	Green walls, vertical façade farming, vegetarian roof restaurants, aquaponics	Fertigation water	meso, macro	7	Northern and central EU	EdiCitNet	2018-2023	https://cordis.europa.eu/project/rcn/216082/factsheet/en
Blackwater	Nutrients	Separate BW collection, centralised treatment with either ammonia sanitisation or AD with urea addition	Concentrated liquid fertiliser	meso	7	Uddevalla[a], Västervik[b], Strängnäs[c], Örebro[d], Västerås[e] Sweden	Centralised BW treatment for >10 households	Implementation since [a,b] 2013, [c] 2014, [d] 2015, [e] 2018	https://pdfs.semanticscholar.org/f5dd/ccffa28be4ab5180eaaaf3a1b168586a00d6.pdf

EdiCitNet: Edible Cities Network Integrating Edible City Solutions for social resilient and sustainably productive cities
HOUSEFUL: Innovative circular solutions and services for new business opportunities in the EU housing sector

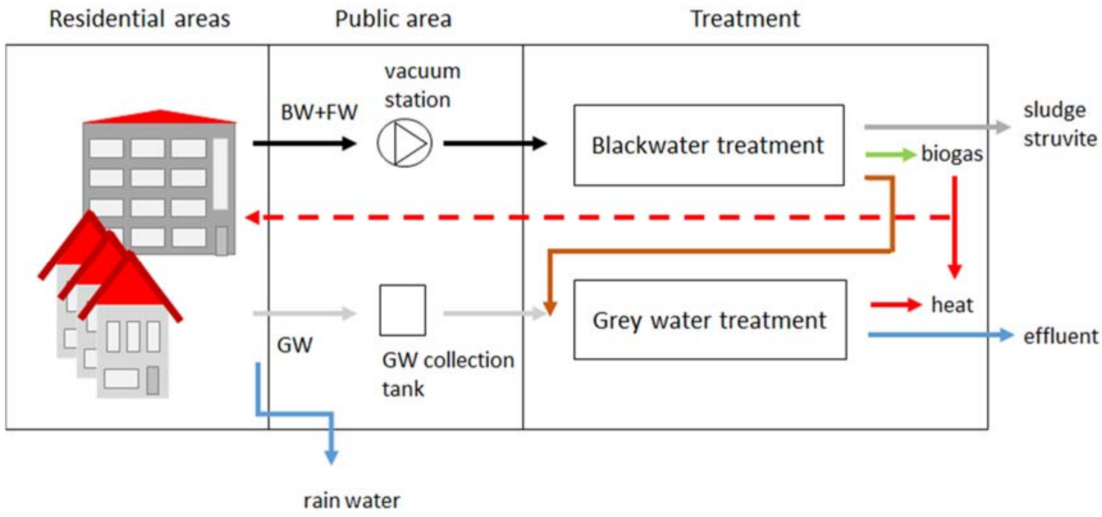

Figure 3: Schematic representation of the projects in Sneek, Netherlands (redrawn and adapted from de Wit et al. 2018)

Similar examples are being set up throughout Europe. For example, the urban renewal project "H+" in Helsingborg, Sweden consists of an old port and industrial areas, in which 320 apartments plus offices for 2000 workers will have source separation systems. In order to reach its future sustainability goals, the city of Helsingborg has established co-operation between the municipal waste, energy and water companies. This Swedish eco-district is part of the *Run4Life* project, together with *De Nieuwe Dokken* district in Ghent, Belgium, and a new pilot at the previously mentioned *Lemmerweg*, and a pilot site in the industrial park of Porto do Molle (Vigo, Spain).

In the *De Nieuwe Dokken* project, the same decentralised treatment scheme will be applied as in the *Noorderhoek* project, similarly as depicted in Figure 3. The multi-step treatment concept is currently being set up for 400 households (1265 IE), which will allow to recover 1600 kg/a struvite, to be used as slow-release fertiliser in the local green areas and urban farming projects, and up to 800 MWh_{th}/a through biogas utilisation and mostly GW excess heat recovery through heat exchangers (part of the NEREUS project, funded by the EU Interreg 2Seas program 2014-2020). In total, about 1/3 of the total heat demand of the urban area (2,1 GWh/a) can be provided by the decentralised treatment plant (Buysschaert et al. 2018). In contrast to the *Noorderhoek* projects, water reuse will be included after-treatment of the GW in a membrane bioreactor (MBR), a cation exchange unit and reverse osmosis (RO) to remove pathogens, nutrients and hardness. In total, more than 30.000 m^3/a water will be reused as process water in a nearby factory. Furthermore, the excess heat of the factory will be recovered by coupling it to the district heating system, thus meeting the remaining 2/3 of the total heat demand. As such, this demonstration project couples recovery of energy and water, and the industrial activity and urban metabolism within a city.

Another example of source separation and recovery of resources at meso level is in the *Rijksgebouw* in The Hague, Netherlands, which houses a.o. the Ministries of Foreign Affairs, Infrastructure and Water Management. The main incentive of the project at the Rijnlaan is to reduce water use and to recover nutrients and energy (Stichting n.d.; Meulman 2019). In the basement of the building source-separated YW and BW of ± 6000 office workers are treated. A part of the YW is collected in water-free urinals (approximately 200 L/day) and more than 95% of the phosphate is recovered as struvite. The struvite is applied in the facility as fertiliser in the enclosed garden of the office building. BW collected in vacuum toilets (3 m^3/day), and in the future combined with food waste (500 kg/day), is digested to produce biogas. The biogas is used in a central heating boiler, which is providing the energy for a hot water buffer tank to heat the building.

In the *Jenfelder Au* in Hamburg, Germany, the so-called *Hamburg Water Cycle*® is installed in a new neighbourhood for approximately 830 residential units. Like in the other above-mentioned projects in Sneek, The Hague, Ghent, and Helsingborg, BW (approx. 12 m³/day) is collected via vacuum toilets and transported via a vacuum sewer to an anaerobic treatment system. In contrast with the other projects mentioned above in the Jenfelder Au, a mesophilic Completely Stirred Tank Reactor (CSTR) is implemented instead of a UASB reactor. Gas production in the Jenfelder Au is increased by adding external substrate from grease separators (max. 30 m³/day with approx. 6% dry matter). The digestate of the CSTR is expected to be used in agriculture after a post-treatment step (to be determined). Greywater will be treated via a fixed bed reactor in a first step. Further treatment processes will be examined in a test unit in order to determine the most effective one for different reuse purposes. The vacuum system is in operation since 2017. The CSTR will be opened in June 2019. The fixed bed reactor will be built starting end of 2019.

In Cressy (Geneva, Switzerland) the cooperative society "Cooperative Equilibre" (CE) realised a 3-storey / 13-apartment building in 2011, which completely separates toilet waste from the water cycle. The toilet waste is collected with non-separating dry toilets, together with wood-chippings as structural material. The greywater is treated on-site in a constructed wetland. The DTM of each apartment is vermicomposted in the basement in a separate 1 m^3 container. Every 6-12 months, approximately 100 litres of pre-composted DTM are manually conveyed to a second composting step in the garden. After completion of the composting process (2 years), the compost is used for fertilizing trees and shrubs in the garden. Since 2011, CE realised two more projects with a total of 103 apartments in Geneva following the idea of decentralised sanitation (including dry toilets) in an urban setting.

In areas with sensitive water recipients in Sweden, it is not allowed to apply (treated) BW as such into the environment. Lately, BW is stored and sanitised in a large tank on a farm prior to reuse as fertiliser. The systems either sanitise the feces with ammonia sanitisation (addition of urea followed by >3 months storage (Nordin et al. 2018), or a combination of biological (Autothermal Thermophilic Aerobic Digestion, ATAD) treatment followed by urea addition. ATAD increases the temperature allowing for less urea addition and shorter treatment time (Nordin and Vinnerås 2015). These centralised BW treatment systems were set up in several municipalities in Sweden. Uddevalla has the largest number of connections with an annual treatment capacity of approximately 3000 m^3, corresponding to 200 to 300 households. In total over 1000 households are covered with this type of system in over ten Swedish municipalities. In this way, nutrients are recycled for agriculture, with less transport of fertilisers and water.

Macro

Source separated GrW is collected separately in many European countries and converted to energy and compost in large-scale centralised AT and composting facilities. In general, the waste treatment facilities apply thermophilic (dry) digestion and the digestate requires post-composting to stabilise. The compost is sold through commercial channels. This technology is used all over Europe to recover biogas/methane from separately collected organic waste and mechanically separated fraction of organic waste from mixed waste. For example, *RCERO* in Ljubljana, Slovenia, is processing waste for around one-third of Slovenia (700,000 people), which amounts to around 150.000 tonnes of mixed municipal waste and 20,000 tonnes of separately collected food waste (Guardian 2019). The combined organic waste is treated in two-stage (thermophilic-mesophilic) plug-flow anaerobic reactors. Biogas is converted via a CHP to electricity and heat, which are both used on-site. The digestate (35,000 t/a) is dehydrated and further processed to produce 7,000 t/a compost.

Centralised methane recovery (Table 5) allows the use of the methane in biogas produced from bio-W, VFY and/or GrW at city level, in order to power e.g. local transport. The city of Reykjavik, Iceland, and its surrounding municipalities, home to about 150,000 inhabitants, collect all organic waste (60% biomass, 40% food waste) in a landfill (a bioreactor is being constructed). The biogas from the landfill has an exceptionally good quality with over 95% methane, which can be used directly in combustion engines. A pipeline from the landfill delivers the methane to gas stations for cars and trucks. About 2% of the personal cars run on methane, all of the city garbage trucks and some company trucks. In 2018, the construction of a modern biogas reactor was started, and it is estimated that methane production will triple, providing biofuel for up to 10% of the cars. A switch of the city buses from diesel to methane is under discussion. These actions are part of an ambitious climate action plan from the Icelandic government. The current government aims to ban registration of new gasoline and diesel buses by 2035 to become carbon neutral by 2040.

Barriers

Barriers for implementation of the above-mentioned concepts are related to the economy (of scale) and safety of operation. For example, the lack of sufficiently safe handling practices in the case of nutrient recovery from faeces or DTM poses a barrier. The removal of organic micropollutants and other contaminants such as microplastics, and hygienic safety of the recovered products are important as well. Recovery of COD and P is easier, since technologies are commercially available, but the recovery of N (and K) as separate product is a problem. Only for streams with a very high N concentration, like urine (YW), N-recovery technologies are available, but during storage of urine a significant part of the nitrogen (about 50%) is potentially lost to the atmosphere due to premature hydrolysis to ammonia in e.g. piping. Stripping of ammonia is technologically feasible but is currently not implemented because of the high energy and chemical demand. Another proven technique for N (and other nutrients) recovery from urine is nitrification (Udert and Wächter 2012), followed by a polishing step with activated carbon and vacuum distillation as applied for the urine collected in the Eawag building. Another barrier for urine collection is the market availability of No-Mix toilets. Several models were taken from the market due to problems during use. Only dry toilets and water-free urinals are proven technologies. Recently, the new NoMix toilet “Safe” was introduced and will probably be marketed at the beginning of 2020. A series of pilot projects in Switzerland and abroad are expected (EAWAG 2019).

When considering the reuse of products from domestic wastewater, for example as fertiliser in (urban) agriculture, the product quality is essential for environmental protection, as well as hygienic safety and user acceptance. In the case of dry toilets, the reuse of compost produced from DTM faces regulatory barriers if the compost is used beyond the own plot of land. Another example of quality issues is contamination with microplastics since the implemented technologies for reuse of digestate and compost from municipal biowaste do not completely remove microplastics (Weithmann et al. 2018). For example, Slovenia allows up to 0,5 % (dry weight) of plastics that is larger than 2 mm in compost and up to 2% (dry weight) of plastics in digestate. Technologies for achieving high-quality products, like membrane filtration, heating, AOP, activated carbon are available but will increase costs. The balance between risks and costs is to be established. In many European countries, the legal framework is currently limiting the possibilities of reusing products from wastewater in agriculture.

Scale is another factor of importance. The concept applied in Sneek, Ghent, and Helsingborg is not suited for single or a few houses. De Wit et al. (2018) calculate that this system becomes competitive with conventional sanitation (references: 30.000 and 100.000 inhabitants) at a scale of around 3.000 inhabitants (price of nutrient products is set at zero). In contrast, the concept applied in Cressy is limited to a maximum of 3 stories, due to space constraints. Furthermore, the existing sanitation infrastructure represents an additional barrier since source separation sanitation requires new infrastructure. Most industrialised countries, however, are characterised by a high-density sewer network (with a very long lifetime) connected to municipal wastewater treatment plants; sewer and wastewater treatment plants have different lifetimes. According to Zeeman (2012), a gradual replacement is the only affordable way to introduce 'New Sanitation' at a larger scale and the development of a transition strategy is required. Close cooperation between involved stakeholders, like established in Sneek, Ghent, and Helsingborg is crucial.

Another important aspect to convince the stakeholders and to remove the roadblocks for implementing new eco-technologies in an urban settlement is the integration of the local community and a sound business model, based on the development of new waste-based and circular value chains. Therefore, Energy Service Companies (ESCO) can be set up to organise the technical maintenance and district services. For example, in the *De Nieuwe Dokken* project in Ghent, Belgium, the ESCO is a mixed private-public-citizens initiative in which the local inhabitants are represented, together with investors and public stakeholders such as the local water utility FARYS. The local community will benefit directly from the revenues of the recovered products and the local district heating system. In the two projects at Sneek, The Netherlands, the conventional division of tasks was chosen in a cooperation between the housing cooperation -responsible for the indoor infrastructure (toilet and piping)-, the municipality -responsible for the outdoor infrastructure (vacuum station and sewer)-, and the water board -responsible for the treatment/recovery technologies. As in Ghent, the inhabitants pay the usual taxes and nothing more. A residents' satisfaction survey was done twice in the project in Sneek. Residents are predominantly satisfied with the system and consider it handy and hygienic, although some people had to get used to the vacuum toilet and kitchen grinder. The provided demonstration and the available information were highly appreciated (Wit et al. 2018).

4.4. Discussion and Conclusion

Resource recovery systems for urban residue streams comprise the collection, transport, treatment/recovery and reuse. It is crucial to consider each step, as e.g. collection and transport will have an effect on applicable technologies for recovery and moreover on quality of products for reuse. When more dilution is allowed during collection and transport, the recovery technology becomes less (energy) efficient and more complex.

Common barriers

Considering barriers mentioned in sections 2.1-3, the realisation of the manifold potentials of NBS for circular cities faces a number of challenges. They can be divided into barriers related to lack of awareness, current legislation, regulations and the organisation of urban infrastructures as well as technical barriers, raising the need for both further technical and social innovation.

Lack of awareness for proven capabilities of NBS

Even though they sometimes perform better than conventional grey technologies (e.g. section 2.1), NBS are de-prioritised. Despite many years of strong scientific track record, the capabilities of plants and microbes to convert nutrients into biomass, clean water and air, extraction of metals and other materials are not yet well known. Especially resource recovery projects using NBS in the narrow sense, i.e. as the European Commission understands them, plant-based systems delivering ecosystem services, are rare. Many NBS projects work to communicate their successes to policy makers and urban planners. Particularly large innovation and demonstration projects have the power to build trust and political willingness for broader implementation of NBS, and to overcome the lack of trust in NBS, even in industry. Capital expenditure for NBS are roughly at par with conventional grey systems (depending on the type of systems compared), but NBS incure lower operational costs and offer additional benefits. Therefore, not only economic, but also environmental and social criteria can incentivise a shift from well-known grey technologies to NBS.

Legislative, regulatory and organisational barriers

Main barriers are related to uncertainties of new system financing (new business models etc.) and the legislation in place (Houston (CSR Europe) et al. 2018). Further, once a resource becomes waste, a resource recovery effort often has to go through waste legislation, thus apply and fulfill all criteria for waste management. Even if applied in small scale, the efforts for application and documentation are similar to the requirements to run large recycling facilities. Also, current legislation does not always allow the direct reuse of secondary products. For example, the Netherlands currently face ongoing discussions on how to deal with compost produced in the city. As local household compost is usually not tested and consequentially not approved, it cannot be easily applied across the city. Standards and legal framework need to adapt to scientific progress, but even research itself (not only implementation) is often already challenged by regulations, when there is no exemption clause in place for research purposes. A certain flexibility of administration processes and obligations could significantly stimulate wider implementation of NBS.

While the recovery of high-value products requires investments available only at macro (and in some cases meso) scale, micro and meso-scale NBS bear the greatest potential for efficient nutrient and clean water recovery through direct reuse. As mentioned above, separate nutrient recovery with NBS is not feasible, but after pre-treatment, direct reuse of NBS-recovered secondary fertigation water and fertiliser/soil conditioner for urban agriculture can keep nutrients (and water) in highly efficient short cycles. This requires new management models in cooperation among municipalities and communities (neighbourhoods), innovation of the division of responsibilities among households/residents/local communities and municipalities (bottom up) coupled with spatial planning and simplification of applicable administrative hurdles (top down). The opportunities of resource recovery for value creation can be leveraged to incentivise decentralised ownership and maintenance.

Large advances have been achieved in reducing the area requirements of NBS, most notably constructed wetlands. Yet, availability of space in cities is still an often cited barrier for functions such as CO_2 capture and wastewater treatment. There is need for more demo case studies and comparable evaluations that can provide standardised data on the ratio of surface area to functional efficiency for different technologies, climate and other conditions to support the planning process. Meanwhile, current planning and design models and tools used for centralised infrastructure approaches are not suitable for decentralised approaches and the integration of NBS into city-scapes. This calls for research to identify optimal scale, management scheme and logistics for existing specific conditions. Spatial planning innovations could facilitate the introduction of NBS to unutilised and underutilised infrastructures (rooftops, façades, indoor spaces). This could, in turn, allow for plant structures at larger scales, thus maximising the aesthetic and stress-reduction potentials of greener cities.

Further, the wide range of secondary end-products can lead to competition among different options. Therefore, there is a need for increased assessments of supply and demand factors, setting optimal configurations of NBS and blended green-blue-grey infrastructure and making the right choice of end-products.

Remaining technical barriers

Recovery of products other than energy is gaining momentum and there is a call for process optimisation towards product purity versus energy yield optimisation (e.g. 'integrated biogas-digestate optimisation', (Logan and Visvanathan 2019)). Many technologies that enable recovery of value-added products are still in development and applied so far only at lab and pilot scales. The next step for these technologies will be scale-up to demo and flagship scales, to prove the hygienic safety of waste(water)-derived products and to further diversify profitable high-value secondary products. Already at this stage, the communication with public and private stakeholders is essential to prepare the market including legislative and regulatory framework for the new bio-products. While NBS can provide essential functions for resource recovery, with significant additional benefits, further processing is usually required to achieve product purity required for commercialisation. Further, the toxicity of some raw industrial or municipal waste streams limits or even prohibits plant and microbial growth. In the field of source-separation and decentralised applications, further research is needed to tackle the challenges mainly related to lack of economy (of scale) and safety of operation.

End-of-life management versus circularity by design

All these solutions look into recovery of secondary resources once they become waste. In this sense, they try to solve problems only at the end of the life cycle and have to take into account that many or most of the actual urban resource stream systems are not designed to be recovered. If you design a system from scratch with circular design in mind, the resource recovery would also be designed to happen with as little energy input as possible. The process can then even be designed to keep the resource value at the highest possible level (Bocken et al. 2016). By mixing resources with others, one has to apply more energy to again recover the value of one resource. In this sense, separation at or close to the source can be favourable for resource recovery purposes, although we should take into consideration the additional infrastructure needs and their associated grey energy (Larsen 2011). Direct metabolisation of organic nutrients from waste streams in agricultural systems can be one of the most favourable options (Capodaglio 2017).

The use of stored solar energy in organic resources for decentralised energy generation can also be a good approach, especially in combination with recovery processes. Since CO_2 is usually the last step in biomass energy systems, such a system can at best be climate-neutral. For more sustainable process designs, one additional aim can be the direct reuse of nutrients by building up biomass and simultaneously converting again CO_2 into biomass, as it is the building block of plants and many other phototrophic organisms. For reasonable carbon capture this biomass should then be either used in long term storage systems like buildings, for furniture etc. or should steadily be composted and integrated as increased soil carbon content. To take resource recovery with NBS to the next level, biorefinery approaches, also at a decentralised level, can be included. In this setting we have to look more into the feedstock quantity and quality of the different resource streams and the conversion to products. In the best case, the decentralised smaller biorefineries at the city level can pre-treat a certain organic residue stream and the conversion to bulk products can happen at a more centralised level (alchemia-nova 2019a). Appropriate logistics and a combination of zero km conversion of nutrients into food and exchange with the surrounding areas can be a good approach for cities. Cities can become “major circular bioeconomy hubs” (European Commission 2018a).

The way forward

In this review paper, we identified projects, technologies, and barriers for application of nature-based solutions for resource recovery in the framework of circular economy in cities. Our recommendations for further efforts are:

- Replication of existing nature-based technologies for resource recovery in more cities and regional prove of concept for enabling further uptake
- Upscaling existing and proven NBS resource recovery systems to bigger areas and for bigger settlements/regions/quarters
- Raise the interest of investment schemes to fund more NBS cases
- Demonstrate and stress the multifunctionality of NBS in new environments (e.g. industrial effluents or processes)
- Cooperate systematically with more actors along value chains and raise awareness

- Share the know-how of NBS openly in developing or underprivileged countries
- Using a value approach model as suitable means for a circular economy evaluation (e.g. value hill as tool (Achterberg and Fischer 2019)) together with other circular indicators (European Commission - Eurostat 2019)
- Comparison of direct reuse (metabolisation) of nutrients in agricultural systems vs. technical recovery and shipping of nutrients back to the fields far away from the source
- Comparing full cost accounting methods to direct nutrient conversion to agricultural produce with conventional farming systems
- Awareness-raising for necessity of nutrient reuse from human systems and the hygienic quality of NBS

4.5. Acknowledgement

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5. WG4 review paper

Urban agriculture as a keystone contribution towards securing sustainable and healthy development for cities in the future

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Abstract

Research and practice during the last 20 years has shown that urban agriculture can contribute to minimising the effects of climate change by, at the same time, improving the life quality in urban areas. In order to do so most effectively, land use and spatial planning are crucial so as to obtain and maintain a supportive green infrastructure and to secure citizens' healthy living conditions. As people today trend more towards living in green and sustainable city centres that can offer fresh and locally produced food, cities become again places for growing food. The scope of urban agriculture thereby is to establish food production sites within the city's sphere; f.e. through building-integrated agriculture including concepts such as aquaponics, indoor agriculture, vertical farming, rooftop production, edible walls, as well as through urban farms, edible landscapes, school gardens and community gardens. Embedded in changing urban food systems, the contribution of urban agriculture to creating sustainable and climate-friendly cities is pivotal as it has the capacity to integrate other

resource streams such as water, waste and energy. This article describes some of the current aspects of the circular city debate where urban agriculture is pushing forward the development of material and resource cycling in cities.

Keywords

Agriculture, circular city, ecosystem services, urban farming, infrastructure, recirculation

5.1. Introduction

Humans today face a plethora of environmental challenges. Some of them are aggravated by concentration of the populations in the cities, all of which constitute a complex set of future challenges; transport of people and goods (i.e. excessive carbon emissions), need for substantial rainfall absorption, high levels of air pollution, urban heat island effect, drinking water supply, waste management, lack of biodiversity. All these challenges results in illness and stress syndromes in the population. Urban agriculture has the potential to contribute towards minimising several of these adverse effects and thus improve the liveability of cities. This review aims to address and clarify some of these aspects, in order to facilitate the implementation of urban agriculture within the context of nature-based-solution (NBS) in circular cities of the future.

Currently, the majorority of the world population growth is in the cities, especially in developing countries. Urban areas worldwide are expected to absorb all the population growth expected over the next four decades and continue to draw in the rural population (United Nations, 2018). While cities today cover about 2-3% of all land area, they consume approximately 75% of the world's energy and generate 80% of the CO_2 emissions (UN, 2018). The cities also utilise large quatities of water, create an enormous quantity of waste and pollute the air. Climate changes are predicted to cause more environmental stressors in the future, while we need to intensify food production (Junge *et al.*, 2014). The required transition will need increased flexibility of the urban environment, more sustainable use and re-use of natural resources as well as the adaptation of infrastructure systems (Herrera-Gomez *et al.*, 2017). All this requires future city development to be smart and to integrate innovative solutions. One key to a more sustainable and healthy city development in the future might be in a relocalisation of the food system and a narrowing of the cities' foodsheds. This idea perfectly coincides with the idea of a circular city, where organic disposals are reused as resources to produce new agricultural products. The contemporary linear understanding of a city, where most independent entities consume, metabolise and dispose of resources, urgently needs – not only but especially in the field of food – a more systematic perspective to solve existing challenges.

In contrast to other infrastructures like water and electricity, the food production, and provisioning system did not get much attention in city planning and are still a neglected field (Pothukuchi & Kaufman, 1999). It needs to be considered that in the process of building the modern city historical ties and links to the localised food system have been disrupted. During expansion, cities lost large areas of their surrounding fertile farmland and have mostly benefited from access to a globalised food system. The consequences of the globalisation of the food system can be seen in an abundance of food but also in the creation of a not sustainable industrialised system that overproduces, pollutes natural resources, declines biodiversity and stimulate obesity and malnourishment (IPBES, 2019, Kennedy *et al.*, 2004). It has also favoured massive path dependencies (Moragues *et al.*, 2017) that can have a significant impact on food security and that needs to be identified and overcome to shape localised, circular economy based food systems for the circular city.

Urban environment conditions, such as air quality, solar radiation and climate are inherently different from rural environments, and these differences may have an impact on crop growth (Eriksen-Hamel *et al.,* 2010). One of the risks for urban farming that stems from air pollution is decreased irradiance, caused by solar dimming, which is caused by increased reflectance of radiation away from the ground, due to air pollutants and aerosols over urban areas. Polluted urban areas can receive 8% less solar radiation than rural areas (Eriksen-Hamel *et al.,* 2010).

This article summarises major aspects related to urban agriculture in order to implement circular agriculture-based schemes in urban settings. What resources exist in an urban biosphere to bring into the context of urban agriculture? The main purpose of urban farming is to produce food within a city, but we also want to pay closer attention to other resources available from urban farming systems, which are usually considered to be waste.

5.2. Urban Agriculture and Circular Cities

5.2.1. Urban food systems: Urban agriculture and urban farming

As an increasingly popular phenomenon in different domains during the last twenty years, Urban Agriculture (Table 1) is discussed in science, policy-making, media and society and its definition is context-dependent (Delgado, 2018). Because of the rapid development of the field, several interpretations of the term 'urban agriculture' exist, capturing nuances within different contexts. Amongst those, two definitions stand out: one from the seminal publication of the United Nations Development Program (UNDP) (Smit *et al.*, 1996); and the other from Mougeot (2001) which provides an extension of the former stressing that it is 'its integration into the urban economic and ecological system' that distinguishes urban from rural agriculture rather than its urban location only.

Smit’s and Mougeot’s definitions are nowadays the most commonly used ones and are valued for their simplicity, openness and implicit inclusion of a circular-city approach.

Urban agriculture spans all actors, communities, activities, places, and economies which focus on primary production in a spatial context categorised as “urban” (Vejre et al., 2015), it can be structured into two sub-groups; urban food gardening and urban farming (Table 1). The common denominator of both is the bio-based output of products, which are harvested and consumed while other effects of urban agriculture on environment and society can be classified as by-products, externalities or co-benefits. These benefits can be classified into four dimensions: food security, economic, social and environmental (McEldowney, 2017), and include contributing to employment, improved education and health, to social inclusion through integrating those at risk of social exclusion. *The business-as-usual farming* operation, as well as non-urban adapted farming, also exist in urban areas (Deelstra & Girardet, 2000; Simon-Rojo *et al.*, 2015). The key benefits include contributing to employment and the development of small-scale rural entrepreneurs; improved education and health; and to social inclusion, through integrating those at risk of social exclusion, such as migrants.

A food system encompasses the full value chain of producing food for human consumption, from agricultural activities and other means, through transportation, handling, processing, storage, distribution and consumption, to organic – including human – waste management and disposal/ reintroduction into productive use (Ericksen, 2008). A food system gathers all the elements: people, environment, infrastructures, inputs, processes, institutions and activities that relate to the production, processing, distribution, preparation and consumption of food, and the outputs of these activities, including socio-economic and environmental outcomes (Fig. 2).

Table 1. Definitions of urban agriculture, urban farming and urban gardening

Definition	**Source**
Urban and peri-urban agriculture (UPA) can be defined as the growing of plants and the raising of animals within and around cities. Urban and peri-urban agriculture provides food products from different types of crops (grains, root crops, vegetables, mushrooms, fruits), animals (poultry, rabbits, goats, sheep, cattle, pigs, guinea pigs, fish, etc.) as well as non-food products (e.g. aromatic and medicinal herbs, ornamental plants, tree products). UPA includes trees managed for producing fruit and fuelwood, as well as tree systems integrated and managed with crops (agroforestry) and small-scale aquaculture.	FAO, 2019
Urban and peri-urban agriculture can be defined as the growing, processing and distribution of food and other products through plant cultivation and (seldom) raising livestock in and around cities for feeding local populations	Game & Primus, 2015
Urban agriculture spans all actors, communities, activities, places and economies that focus on biological production in a spatial context which - according to local standards - is categorized as "urban". Urban agriculture takes place in intra- and peri-urban areas and one of its key characteristics is that it is more deeply integrated into the urban system compared to other agriculture. Urban Agriculture is structurally embedded in the urban fabric; it is integrated into the social and cultural life, economics and the metabolism of the city.	Vejre *et al.*, 2015
Urban agriculture is growing, processing and distribution of food or livestock within and around urban centres with the goal of generating income.	McEldowney, 2017 Roggema, 2016
Urban agriculture is an industry that produces, processes and markets food and fuel, largely in response to the daily demand of consumers within a town, city or metropolis, on land and water dispersed throughout the urban and peri-urban area, applying intensive production methods, using and reusing natural resources and urban wastes, to yield a diversity of crops and livestock.	Smit *et al.*, 1996
Urban agriculture is an industry located within (intra-urban) or on the fringe (peri-urban) of a town, a city or a metropolis, which grows and raises, processes and distributes a diversity of food and non-food products, (re-) using largely human and material resources, products and services found in and around that urban area, and in turn supplying human and material resources, products and services largely to that urban area.	Mougeot, 2001
Urban food gardening encompasses agricultural activities with generally low economic dependence on the material outputs while using food production for achieving other, mostly social, goals.	Simon-Rojo *et al.*, 2015
Urban farming refers to intentional business models taking advantage of proximity to the city by offering local or regional agricultural products or services. The importance of the production in proportion to the other societal benefits can vary strongly (...), both, the production-oriented side or the co-benefit-oriented side may prevail depending on the individual practices of an urban farming operation.	Pölling *et al.*, 2015

5.2.2. Continuous Productive Urban Landscapes (CPUL) and growing space typologies

Agriculture is space and time-bound: plants and animals grow in a certain place and at a certain pace. Thus finding space in cities and city-regions is a prerequisite for urban farming. While some of these spaces are well known, such as traditional farming land, allotment gardens or family gardens, other spaces might offer the potential for urban farming in a permanent or a temporar way (Table 2).

The *Continuous Productive Urban Landscapes (CPUL City)* concept (Viljoen, 2005) describes an urban future based on the planned and designed introduction interconnected urban landscapes defined by urban agriculture into existing and emerging cities. It follows a systemic approach using quantifiable and qualitative arguments to propose that urban agriculture contributes to more sustainable and resilient food systems while also adding beneficially to the spatial and social quality of the urban realm (Bohn, 2016). A CPUL aims to interconnect urban food-producing landscapes within a city and to the citizens on the one hand and to connect these landscapes to the rural hinterland on the other and thereby facilitates activities across all parts of the urban food system.

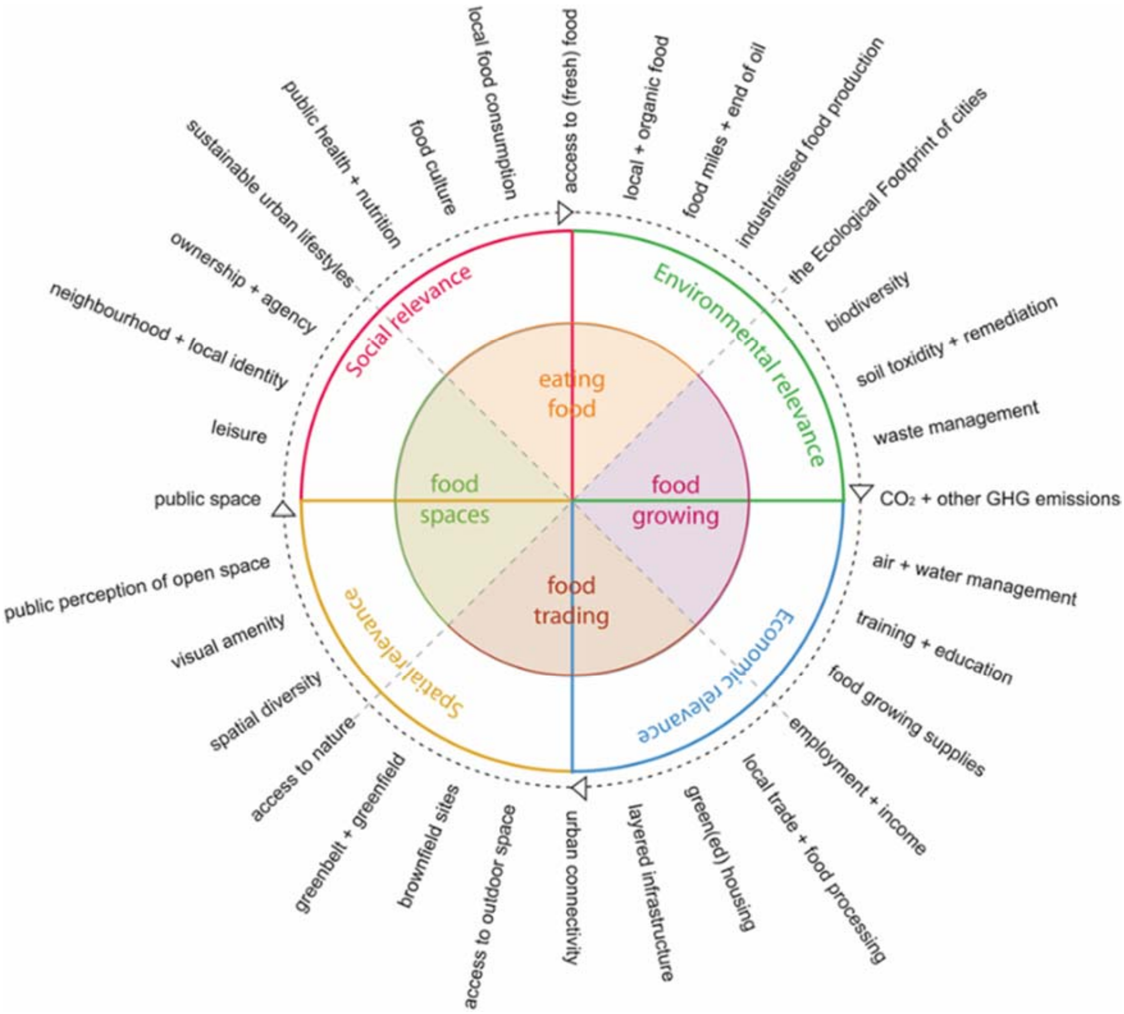

Figure 2. This diagram shows the many links food, and the food system has with most aspects of urban life. It gives weight to spatial aspects related to urban food, including those related to urban agriculture *(source: Bohn and Viljoen, 2009)*.

This was illustrated also by the outcomes of the studies that evaluated the stakeholder perceptions of rooftop agriculture in Berlin and Barcelona (Sanyé-Mengual *et al.*, 2015a; Specht *et al.*, 2015a,b) and concluded that even if there are a number of potential risks assossiated with the urban farming system, stakeholders establish new market structures (e.g., short supply-chains) to overcome barriers and to ensure a socially accepted development of this new form of urban agriculture.

5.2.3. Relationship between urban agriculture and green infrastructure

The significance of urban agriculture has been highlighted by a set of UN-Habitat reports on how cities can work with nature. In these reports, it is argued that to achieve environmental and economic resilience; biodiversity needs to be reinstated in urbanised areas (UN Habitat, 2012). One of the major co-benefits of urban agriculture lies in its contribution to the urban environment, green infrastructure and the related ecosystem services (Viljoen 2005; Santo *et al.*, 2016; McEldowney, 2017; Samson *et al.*, 2017; Golden *et al.*, 2018; Piorr *et al.*, 2018).

Green infrastructure is a significant element in European planning policies on all scale levels. It is one of the primary tools for achieving the EU Biodiversity Strategy 2020 (European Commission, 2011) as well as smart, sustainable and inclusive growth defined by the Europe 2020 Strategy (European Commission, 2010). Urban agriculture contributes to the ecosystem services of green infrastructure as a provisioning service for food, energy and raw materials, as well as through a range of other ecosystem services (Table 3).

Table 2. A typology of growing spaces for urban farming (adapted after Santo *et al.*, 2016; Simon-Rojo *et al.*, 2015)

Typology of the city area	Urban farming spaces in cities	Examples and references
Soil-bound spaces	Arable land	
	Allotment gardens	Individual gardening (commune patch)
	Family gardens	Individual gardening (private patch)
	Squatter gardens	
	Community gardens	
	Parks and other public green spaces	Van Leeuwen *et al.*, 2010
	Urban derelict land	Brown *et al.*, 2016
	Guerrilla Gardening	Manchester, UK*
Mobile and soil-independent systems	Growing boxes and bags	
	Mobile containers	e.g. PAFF Box (Delaide *et al.*, 2017)
Building bound spaces	Rooftops:	Buehler & Junge, 2016
	- Open rooftops	
	- Covered rooftops	Glasshouses
	- Flat roof	
	- Roof with inclination	
	Facades:	
	- Open facades	
	- Covered facades	Glasshouse
	Building extensions:	
	- Balconies	
	- Window sills	
	Indoor spaces with/without artificial lighting	
Water bound spaces	Urban streams	
	Urban stagnant waters	e.g. ponds, lakes
	Amphibia systems	e.g. floating islands

*http://www.urbanallotments.eu/fileadmin/uag/media/STSM/Binder_shortreportSTSM_final.pdf

Tóth (2017) has shown the quantitative importance of urban agriculture in the green infrastructure networks of four differently structured European urban regions (Dublin/Ireland, Sofia/Bulgaria, Ruhr Metropolis/Germany and Geneva/Switzerland). The regional green infrastructure systems of urban regions, which form a continuous system of open spaces often described as spatially coherent figures (green corridors, green wedges or green belts), can, in most cases, only achieve this claim of continuity if they include the semi-natural areas used for urban agriculture. Urban agriculture is an indispensable component of green urban systems.

5.2.4. Biodiversity and ecosystem services

Due to their population density, urban areas have a very high demand for multiple ecosystem services. Moreover, cities play an essential role in climate change mitigation and is increasingly vulnerable to climate change impacts (Rosenzweig *et al.*, 2010). To achieve well-functioning circular cities that ensure good quality of life for their residents, it is urgent to safeguard biodiversity and improve the supply of regulating, cultural and supporting ecosystem services (McPhearson *et al.*, 2015). Environmental benefits associated with urban agriculture include increased biodiversity, mitigation of the 'urban heat-island effect' and a reduced risk of flooding (McEldowney, 2017). Urban agriculture has an enormous potential to provide multiple ecosystem services in addition to food production, significantly contribute to the functioning of green/blue infrastructure and mitigate climate change (Lwasa *et al.*, 2014). However, to maximise multiple benefits that can arise from urban food production, urban agriculture has to adopt sustainable farming practices (for instance organic farming, use of agroecological approaches), ensure functional integration to the urban fabric, and safeguard biodiversity key areas (IPBES, 2019). This applies to both small-scale food production for personal or community use (urban food gardening) as well as commercial farming in urban areas (urban farming). Table 3 shows the contributions of urban agriculture as this is what the green infrastructure is based on.

Table 3. Contributions of urban agriculture as green infrastructure (GI) based on Timpe *et al.* (2015)

Ecosystem Services, TEEB[¤], 2015:	European Commission, 2013a,b:	
ES Benefits Group	**GI Benefits**	**Possible Contribution of urban agriculture**
Provisioning services	Multifunctional resilient agriculture and forestry	Providing food, fibre and biomass and enhancing pollination.
	Investment and employment	Employment in agriculture, investment in agricultural enterprises and buildings, productive and maintained land as contributions to a better local image.
Cultural services	Tourism and recreation	A broad range of recreational activities proposed on farms and in gardening associations, farms and gardens as a destination.
	Education	Agriculture as a teaching resource and «natural laboratory».
	Health and wellbeing	Farm work and gardening as activities for physical and mental health, access to healthy local food.
Regulation services	Enhanced efficiency of natural resources	Maintenance of agricultural soil fertility, pollination through urban beekeeping.
	Climate change mitigation and adaptation	The cooling effect of agricultural areas, carbon storage in soils.
	Water management	Groundwater recharge and purification under agricultural soils, stormwater retention.
	Land and soil management	Reduction of soil erosion, maintaining/enhancing soil's organic matter, increasing soil fertility and productivity, mitigating land consumption, fragmentation and soil sealing.
	Disaster prevention	Flood hazard reduction through stormwater retention and agricultural polders, erosion control.
Habitat	Conservation benefits	Maintenance of agrobiodiversity, maintenance of agricultural habitats.
	Low-carbon	Short-chain food provision, local bioenergy from agriculture.

[¤]The Economics of Ecosystems and Biodiversity – TEEB.

5.2.5. Air pollution risk and agronomic considerations on urban farming

Pollution risks of urban food farming, understanding food production outsides in open city spaces, can be combined with risk for food safety and content of pollutants in the food products. There are a few articles on this topic but more research is needed to fully understand the risks. There are three primary risks of gardening in cities and urban environment; soil, water and air pollution. For air pollution, there are three categories; 1) not accumulated in plants, 2) transport-vectors of pollutants and 3) pollutants that are taken up in plants. Within a city, many sources of pollution are present: e.g. traffic, industries, heating (Ortolo, 2017).

Fruit trees are most affected by air pollution. The air pollution in China has caused damage to fruit trees by delaying sprouting, shortening the flowering period, accelerating senescence and reducing CO_2 assimilation. This resulted in a reduction of fruit numbers and premature dropping of fruit (Zheng *et al.,* 1991; Boa et al., 1997). High ozone concentrations cause chlorotic spotting, necrotic lesions and premature senescence in trees, vegetable crops and cereals (Rich, 1964; Krupa *et al.,* 2001). The ambient air pollutants (SO_2, NO_x, SPM and RSPM) caused a significant reduction in total chlorophyll, carotenoid, ascorbic acid, plant height, shoot fresh weight, root fresh weight and yield of wheat and mustard crops grown at polluted sites (Chauhan & Joshi, 2010). The elevation of CO_2 concentration has been shown to increase the yield of crops under laboratory conditions, but in reality the degree of growth stimulation is dampered in the environment due to high temperatures and increasing tropospheric O_3 (Ainsworth, 2008). A case study in Varanasi, India concluded that gaseous pollutants such as SO_2, NO_2 and O_3 have damaging effects on the yield of wheat, mustard, mung and palak plants (Agrawal *et al.,* 2003).

Apart from ozone, it can be difficult to identify the causal link between a specific gas and damage to crops, which is why there aren't many studies made on this topic (Hamel *et al.,* 2011). A study in Greece used a combined air quality and GIS modelling approach to estimate crop damages from photochemical air pollution (O_3) and depict the corresponding economic damages. Total economic damage to crops turned out to be significant and estimated to be approximately 43 M€ for the reference year (Vlachokostas *et al.,* 2010).

Suspended particulate matter has the most significant effect on crop yields and the quality of the crops. Atmospheric pollutant deposition has been noted as the most common pathway for lead contamination of leafy greens in Uganda (Nabuloetal, 2006). A study in Nigeria of the correlation between traffic emissions of Cd, Cu, Cr, Ni, Pb and Zn near a highway and the concentration of heavy metals in the vegetation and soil samples near the highway has been conducted. The study showed that roads have a significant effect on heavy metal accumulation in vegetation (Ndiokwere, 1984).

5.3. Material and Resource Management

5.3.1. Resource management

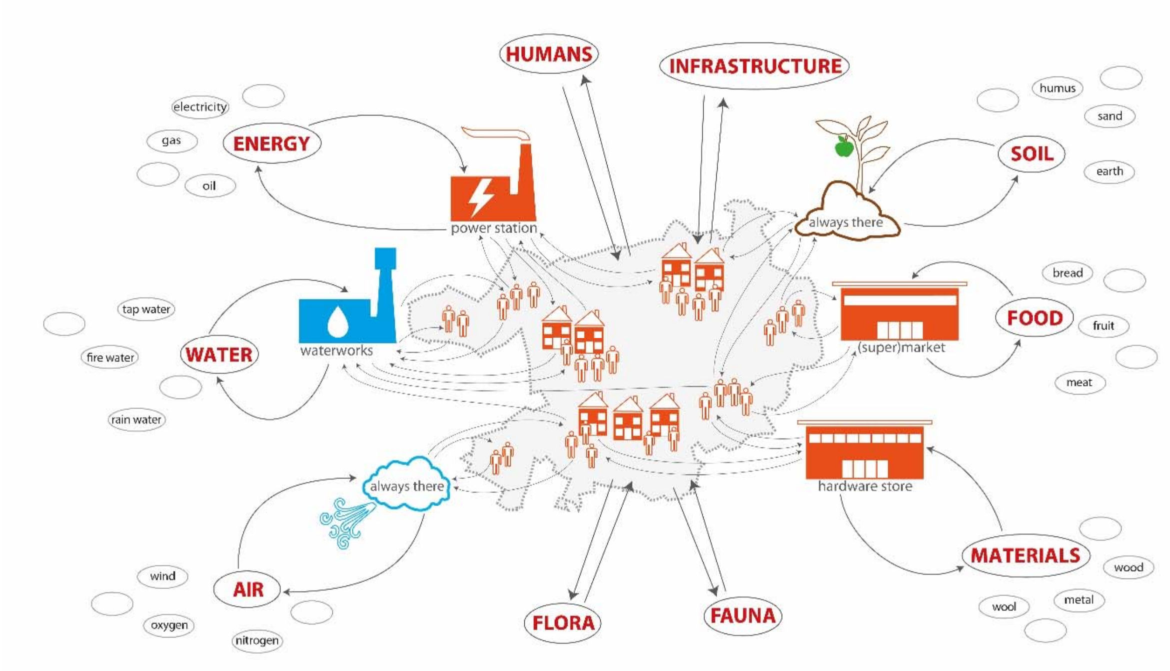

Figure 1. Resource streams in urban metabolism. This diagram shows how food and the food system are located as part of other resource streams into and out of the city *(Source: Bohn, 2016)*.

Resources such as water, food and energy are what cities need to function (Fig. 1). The entirety of resource streams and their interactions with each other, citizens and urban space are incredibly complex. Despite some of these resources being nature-based, most resources flows are linear: they are used and then disposed of these resources. This linear urban metabolism (Rogers, 1997; Daigger, 2009) dominates in contemporary towns and cities all over the world, and it is causing a plethora of problems. The circular approach explores how to manage resources by reducing, reusing and recycling. As a consequence, this leads to redesign of the urban, peri-urban and rural space, and to a new conceptualisation of their interlinkages. One of the critical elements in the development of closed-loop designs is a localised food systems approach, which also links to a broader understanding of a (peri-) urban water-energy-food nexus (Fig. 1).

5.3.2. Growing media

Soil is the «default» growing substrate for plants, however urban soils are often degraded (De Kimpe & Morel, 2000) and do not enable healthy plant growth. Therefore, replacing the soil with other substrates in urban environments, can contribute towards healthy produce. Based on chemical properties growing media can be split in organic and inorganic (Table 4). The most important physical property is particle size, which affects the physical characteristics (e.g. porosity, water holding capacity, air space). Well-balanced physical and chemical properties of the growing media induce the plant growth and also promote biological activity (Maucieri *et al.*, 2019). Also, it should be free of weeds, pathogens and toxins.

In circular cities of the future, it is important to focus on renewable materials from agricultural, industrial and municipal waste streams to identify beneficial and environmentally sustainable materials as growing media (European Commission, 2019). It is environmentally beneficial to reuse and recycle renewable materials, and contributing to the circular economy (CE) which is, together with bioeconomy, supporting concepts in order to facilitate the transition to a sustainable society.

Table 4. Overview of substrates used in urban agriculture

Substrate	Description	References
Soil		
Urban soil	Urban soil is often exposed to many strong influences which result in contamination and structural deterioration. Among others, urban soils can be contaminated with hydrocarbons and-or heavy metals, which can accumulate in produce and compromise human health. Before growing food in urban soils, soils have to be tested for exceeding the contaminant limits. Contaminated soil can be remediated with physical (soil excavation, washing and vapour) and biological (microbial, fungal remediation, phytoremediation) techniques.	Clarke *et al.*, 2015; Jean-Soro *et al.*, 2015; Schwarz *et al.*, 2012.
Substrates of organic origin		
Peats	Result from anaerobic decomposition of peat mosses under waterlogged conditions. Depending on conditions under which they were generated, peats possess superb physical, chemical and biological properties suitable for plant growth. However, peat bogs an endangered ecosystem and are mostly under protection. Therefore, peat substitutes should be used preferentially.	Krucker *et al.*, 2010; Michel, 2010; Maucieri *et al.*, 2019.
Peat alternatives	Motivated by environmental, but also technical issues, many peat alternatives have been investigated, for example, ground fresh rice hulls (GRH), anaerobic digestion residues (ADR), coir dust or cocopeat, wood fibre substrates. Some have excellent properties to be used in soilless culture for the production of seedlings and transplants.	Schmilewski, 2008; Zanin *et al.*, 2012; Gruda *et al.*, 2006.
Compost	The result from the aerobic decomposition of plant material. When mature, composts ensure minimal medium shrinkage, oxygen consumption, nitrogen immobilisation and phytotoxicity. A wide array of organic waste can provide feedstocks for composing, this being the reason why it can be widely implemented also on a household level and in the cities.	Maher *et al.*, 2008; NiChualain *et al.*, 2011; Raviv, 2013; Barrett *et al.*, 2016; Perez-Murcia et al., 2006.
Vermicompost	Results from the composting process using various species of earthworms and organic materials, such as plant and food waste.	Bachman *et al.*, 2008.

Pyrolysis biochar	Biochar resulting from the pyrolysis of organic matter. It can be used as a soil amendment or as a part of substrate mixture. Pyrolysis process requires predominantly dry substrates (e.g. straw, faeces, wood chips).	Bruun *et al.*, 2012; Gold *et al.*. 2018.
HTC (Hydrothermal Carbonization) biochar	Biochar resulting from hydrothermal carbonisation of organic matter. HTC also functions with predominantly wet substrates like sewage sludge or whey. It can be used as a soil amendment.	Escala *et al.*, 2012;
Inorganic media		
Sand and gravel	The coarse fractions of the soil minerals have particle size 0.02-2.0 mm (sand), and 5-20 mm (gravel). Coarse sand is preferred as a substrate for plant growth and rooting cuttings while fine sand is preferred for seedling production. Quartz (SiO_2) is the most common component of the sand fractions. Due to environmental constraints, natural sand dunes extractions limits the use of sand as a growing media. Gravel is less used due to the low water holding capacity and heavyweight.	Lennard and Leonard, 2006.
Perlite	A volcanic based inert, lightweight mineral with high porosity. It is produced at temperatures above 1000 °C. It has a pH of 7.0-7.5 and contains no minerals available for plant needs. It is produced in various particle sizes. It is used in mixtures with other media. Similar to perlite, pumice is another volcanic based material.	Verdonck *et al.*, 1981; Maucieri *et al.*, 2019
Zeolites	Are usually formed by the metamorphosis of volcanic rocks but also from non-volcanic materials in marine deposits or aqueous environments. They have high ion exchange, adsorption, hydration-dehydration and catalysis properties, therefore also high pollutant removal capacity. Zeolite is used as a growing media component.	Ming and Mumpton, 1989; Harland, 1999.
Vermiculite	A natural clay mineral with water molecules within its structure layers. It is produced similarly to and has similar physicochemical properties as perlite. It is produced in several particle sizes, which affects the physical characteristic of the material (e.g. porosity, water holding capacity, air space). Vermiculite has a pH of 7.0-7.5, low electrical conductivity (EC), and contains potassium (K) and magnesium (Mg).	Verdonck *et al.*, 1981; Maucieri *et al.*, 2019
Mineral wool / Rockwool	It is industrially produced by melting minerals at up to 1600 °C and spinning the molten mixture at high speed into thin fibres (~ 5 µm diameter). Rockwool is often used in soilless cultures, providing advantages (sterile, inert and consistent in performance) but also limitations (lacks nutrient buffering capacity) in its use. However, it is a non-renewable resource, and the possibilities for recycling are currently limited.	Verdonck *et al.*, 1981; Maucieri *et al.*, 2019
Nano-fertilisers	Nanotechnology can be used in the production of fertilisers due to the high efficiency and the homogenous distribution of nano-form of the nutrients. Nanoparticles (1-100 nm) confer improved efficacy in their physicochemical properties. However, the plants response to the nano-fertilisers is significantly different and dependent on plant type.	Torabian *et al.*, 2017; Nair *et al.*, 2010.
Light expanded clay aggregate (LECA)	Leca (ISO 10-20) is a building material made of clay, burnt and converted into small, porous, hard-surface spheres. The balls are used in growing beds for plants, as insulation, and as raw materials for blocks, pipes and other elements.	Maucieri *et al.*, 2019

5.3.3. Deposition of pollutants in soil

Particulate air pollutants are usually settleable by gravity and are deposited on the ground through wet and dry deposition. They cause acidification, salinisation and high heavy metals concentrations. To assess the influence of air pollution on soil composition, a study of heavy metals concentrations (Cd, Pb, Ni, Sb and Bi) in the settleable particulate matter in two locations in Spain has been performed. The study showed significant seasonal variability for heavy metal content and a strong dependence on rainfall in the area. The maximum values of heavy metals were measured in spring or autumn when there was the highest rainfall (Soriano *et al.,* 2012).

Werkenthin *et al*. (2014) reviewed studies of metals in European roadside soils and concluded that the highest levels of Cr, Cu, Ni, Pb and Zn, were determined in the topsoil layer, and located in the first 5 m beside the road. Generally, the influence of traffic on soil contamination decreased with increasing soil depth and distance to the road. .

Based on these findings, there are some concerns about the quality of food produced in urban environment. The suitability of food produced in close proximity of urban traffic or other sources of pollution, should be closely examined.

5.3.4. Available water resources

Treated domestic or municipal wastewater, also designated as reclaimed water, is used worldwide as an alternative water source. In some countries is even used as a water source for drinking water, such as in Singapore and Texas-USA (Yi *et al.,* 2011). In California-USA, in full-scale large dimension projects, reclaimed water is being used for irrigation. In the near future, when the health and social objections existing presently in Europe, are overcome by the overwhelming current efficiency of advanced wastewater and water treatment technology, reclaimed water will become one of the most important sources of urban water (Norton-Brandão *et al.,* 2013).

Linking urban water usage to urban agriculture has the potential to be mutually beneficial. Availability of safe alternative water sources may; (i) facilitate higher uptake of urban agriculture, (ii) proper use or reuse of municipal water which may improve stormwater and wastewater management, reduce sewer overload and nutrient loads to urban rivers and allow sewer mining for resource recovery (e.g. nutrients) (Tahir *et al.*, 2018; Voulvoulis, 2018). However, any long-term studies on the combined benefits, health risks and robustness of reuse systems in farming projects appear to be missing and are the research focus of only very few current projects, such as the case of Roof Water Gardens project (Million *et al*., 2016) and the HOUSEFUL project on innovative circular solutions and services for the housing sector (www.houseful.eu).

Urban agriculture in a circular city should meet its water requirements by water resources which originate from within the urban watershed (Fletcher *et al*., 2013; Tahir *et al*., 2018; Voulvoulis, 2018; Pratt *et al*., 2019); and, in this framework, tap water should not be the first choice. More appropriate resources may comprise natural rainfall for rainfed farming, the usage of rainwater temporarily stored in cisterns – also called rainwater harvesting – or the usage of urban wastewater. Untreated urban wastewater is usually not considered in farming projects in developed countries due to significant public health concerns for farmers and consumers (Khalil & Kakar, 2011; Drechsel et al., 2015; Khan et al., 2015; Okorogbona et al., 2018). However, the usage of treated or untreated greywater – wastewater generated in households or office buildings from streams without fecal contamination – (i.e. all streams except for the wastewater from toilets) recently received more attention as it also reclaims fertilizer resources such as nitrogen, potassium, calcium, magnesium, sodium and phosphorus (non-renewable resource) (Qadir et al., 2007; Chen et al., 2013; Oteng-Peprah et al., 2018). Some studies have shown that nutrient-rich wastewater can be productively reused in urban and peri-urban agricultural systems, contributing to crop yield and improving soil fertility, thus enhancing the resilience of urban areas (Murray & Buckley 2010; Drechsel et al., 2015).

5.3.5. Irrigation water requirements

Some projects – including Urban GreenUP (www.urbangreeup.eu), CITYFOOD (www.cityfood.igb-berlin.de) and TUNESinURB (www.tunsinurb.org) – have studied the sustainability of gardens, edible gardens and urban farming (Paço *et al*., 2019). The knowledge on irrigation water requirements considers a scenario where rainwater is harvested and stored for the irrigation season as a possible alternative or supplement to the current irrigation sources in Mediterranean cities, mainly where rainfall is less than 500 mm/year, concentrated in some months in wintertime, and the current water source is tap water. However, technical solutions to accommodate the water volumes involved, in what regards building structure and architecture, are needed as well as water pumping and irrigation systems costs analysis. Urban landscapes for environments with hot/dry summers can benefit from the use of low water requirements plants, namely native species (Paço *et al*., 2019). It is essential to quantify the water requirements of such species as little information exists.

5.4. Cultivation Techniques and Production Systems

The lack of soil fertility, available rural and urban land space, agricultural sectors long distances from the urban centres provide the challenges and opportunities to develop urban agriculture. Therefore, in addition to conventional growing techniques in soil, different soilless techniques are implemented.

5.4.1. Soilless cultures and hydroponics

Soilless culture is a technique to grow plants without soil, using inert media (e.g. rockwool, clay pebbles, coconut fibres) or no media, and supplied with a nutrient solution (i.e. water and soluble nutrients). Currently, the terms soilless culture and hydroponics are used as synonyms; however, hydroponics originally meant cultivation in a nutrient solution without supporting growing substrate as soil (Zanin *et al.,* 2009).

In the horticulture, soilless cultures are the most important cultivation methods for effective production in greenhouses (Jensen *et al.*, 2010). The criteria for classification of soilless cultures are: presence and properties of substrates and containers, vertical or horizontal system, location (greenhouse, garden, integrated into the building), how the nutrient solution is administered to the plant (dripping watering, immersing in stagnant solution or through mist spray), and type of water circulation (open or closed systems) (see also Maucieri *et al*., 2018, Maucieri *et al*., 2019). Among the newest hydroponic technologies are "aeroponic systems", drip irrigation and nutrient film technique (NFT). The most frequently cultivated species in this type of culture are vegetables, herbs and medicinal plants. Under suitable conditions, decorative plants (e.g. roses, gerberas, carnations) can be grown as well (Savvas & Passam, 2002).

5.4.2. Aquaponics

To succeed with integrated production units, producing more than one type of product for sale, are highly sought. Aquaponics is a production technology which combines aquaculture production in recirculating aquaculture systems (RAS), with the soilless cultivation of plants (Graber & Junge, 2009, Rakocy, 2012, Monsees et al., 2017)). The effluent from the fish (or other aquatic organisms) production unit supplies the horticultural unit with water and nutrients for plant growth. Since the nutrient profile can be individually adjusted by measuring the nutrient profile and adding missing nutrients, multiple plant species can be grown as monocultures or in polycultures (e.g. intercropping, companion planting, (Maucieri *et al.,* 2017)). A wide array of vegetables (Graber & Junge 2009, Monsees et al. 2019), flowers (Agha Rokh 2008), fruits (Schmautz *et al*., 2019), herbs (Nozzi *et al*., 2018) and berries (Villarroel *et al*., 2011) can be produced and serve the local market. Pest and disease management focuses on prevention and is based on principles of integrated pest management and organic agriculture (Némethy *et al*., 2016). Very different system set-ups can be customised to diverse requirements; high-/low-technological, commercial sizes, backyards systems, education and hobbies set-ups (Maucieri *et al.,* 2018). Most common are freshwater systems on-land (Skar *et al*., 2015).

5.4.3. Vertical farming

Vertical farming is a system of farming whereby living organisms (animals, plants, fungi and other forms of life) that are cultivated for food, fuel, fibre and other products or services are artificially stacked above each other, vertically. The concept of vertical farming is integrated into the urban production of fresh produce. These systems are very efficient in terms of land use due to reduced dependency on land resources (Pérez-Urrestarazu *et al.*, 2015). Moreover, vertical farming can contribute to the effectiveness of the arable area for crops by constructing a high-rise building with many levels on the same footprint of land (Despommier, 2010). Soilless culture and hydroponics can add inputs to that direction, with considerable savings on water, minerals and phytochemicals through the sustainable cultivation cropping systems.

5.5. Policies, Regulations, Governance

The governance of UA may primarily include such issues as land, land use, access, food and ecosystem health, education and the environment as well as heritage and cultural practices (Corcoran *et al.*, 2015). Prové *et al.* (2015) established a conceptual framework for urban agriculture governance processes and identified characteristics which influence the processes of management of urban agriculture initiatives. The three levels of this framework, which include the main features of the governance of urban agriculture are: (i) **Urban context** (including the local geographic situation, economic and political situation, the agricultural context and the status of urban-rural relations); (ii) **External governance characteristics (**including public policies, partnerships, legitimation processes); and (iii) **Internal governance characteristics**, which include the project objectives, spatial scale, temporality, actors and resources (land, finance and knowledge mobilised in the project). All these are embedded into the local situation, characterised by geography, climate, economic and political situation, cultural values and urban-rural relationships.

Of course, public policies that influence these three categories are very different (Figure 5). For example, urban gardening is not affected by agricultural policy. Thus, the analysis of governance will focus on urban agriculture initiatives with the active involvement of professional farmers and public policies that influence these initiatives, mainly agricultural policy and planning. The focus will be on the integration of agriculture and agrarian actors in the development of cities and especially in regional planning (UNUIAS, 2010).

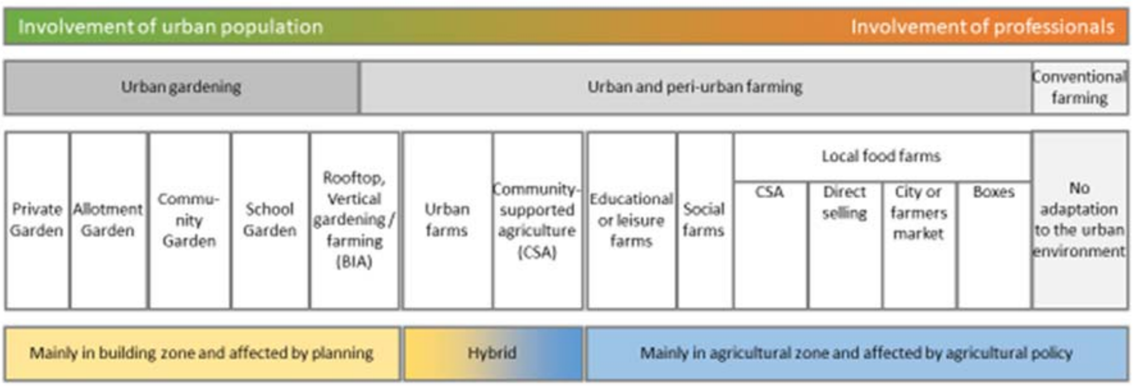

Figure 5. Typologies and social aspects of urban agriculture initiatives (adapted after Mumenthaler, 2015).

There are huge variety of UA activities and interventions, which can involve domestic, public and commercial projects, involving actors of different resources, skills, orientations and motivations. In general, because of intrinsic hybridity of UA governance, the policy linkages are often unexplicit and not considered strategical either by national governments or municipalities (Corcoran *et al.*, 2015).

5.6. Business Models in Urban Agriculture

5.6.1. Economically viable urban food production

City environments influence agriculture (Heimlich and Barnard, 1992). Farmers located in such areas will have to adjust their farming to exploit all opportunities and to counter most of the restraints' (van Huylenbroeck *et al*., 2005). The main hurdles for urban agriculture can be summarized into land-related constraints, conflicts caused by improper behaviours of urban dwellers, and economic incentives within cities outside farming. However, urban areas hold chances for economically viable food production strategies. Little attention was given to these positive effects of cities and agglomerations on farming in the past (Beauchesne and Bryant, 1999). Cultivation, processing and marketing of urban farming's food and non-food products take place in an environment of the highest demands (McClintock, 2010). The potential of nearby and easily accessible large consumer groups, the concentration of particular societal demands and trends, and the innovative milieu in cities offer favourable framework conditions for local and short marketing channels both for agricultural products and for the provision of services associated with farming.

5.6.2. Urban influence on business performance and success

Cities and agglomerations increasingly incentivise farms to adjust to the urban conditions aiming to achieve profitability and business success. By doing so, farms increase chances to maintain economically viable or enhance their business performance (van Veenhuizen and Danso, 2007). When farms do not adjust adequately to the multifaceted and dynamic urban influences, they increasingly tend to give up or turn into part-time or hobby farming with main revenues originating outside of agriculture (Zasada, 2011). Gardner (1994) says that commercial farming in urban areas is surviving and even prospering when adjusting adequately to the cities. Thus, the diversity and complexity of urban influences result in a variety of city-adjusted farm strategies. Urban agriculture has been identified as being more diversified, polarised and multifaceted than elsewhere (Zasada, 2011). Common strategies of urban agriculture focus on high-value production, product niches, short supply chains, Alternative Food Networks (AFNs) and the provision of services connected with agriculture (e.g. Heimlich and Barnard, 1992; Gardner, 1994; Mougeot, 2000; Bailey *et al.*, 2000; Houston, 2005; Zasada, 2011; Aubry *et al.*, 2012; Aubry and Kebir, 2013; Bryant *et al.*, 2013). Specialisation, niche production, multifunctionality, food chain management, quality of food, and embeddedness of food are listed by Wästfelt and Zhang (2016) as appropriate for urban agriculture activities. By focusing on the consumer side, Barbieri and Mahoney (2009) and Inwood and Sharp (2012) highlight that better chances of farm business survival and development exist for those city-adjustments which apply immediate consumer orientations and relationships. Agricultural innovations often take place on farms within metropolitan areas and subsequently diffuse into rural areas (Beauchesne *et al.,* 1999; Prain *et al.,* 2007; Elgåker *et al.,* 2008; Zasada, 2011).

5.6.3. Business model classifications

The heterogeneity of urban farming's city adjustment strategies, as well as the lack of business model, approaches are highlighted by Boons and Lüdeke-Freund (2013). Both have been providing the basis for the recent emergence of business model classifications in urban agriculture since a few years. While economies of scale is still an essential rural farming business model to stay competitive under intense cost pressures in the food sector, urban agriculture business models have to distinguish by adjusting to cities and move away from mainstream commodity market and global prices mechanisms. New business concepts have emerged on established (peri-)urban farms and also by newcomers and start-ups in urban agriculture. The specifically challenging, but also enabling urban conditions encourage innovations in farming, and result in the appearance of business models, which in many respects are different from rural farms. Product differentiation and enterprise diversification are the prevailing business models, but new forms of and new actors in urban agriculture raise experimental, shared economy and experience to emerging business models (van der Schans, 2015; Pölling *et al.*, 2015).

The business model differentiation is frequently applied in urban areas to create distinctions in production, processing and marketing from the bulk market. Short food chains, especially direct sale, along with premium prices for specific product features (for instance super-fresh, ethnic, tasteful) are based on personal, transparent and honest producer/consumer relationships. Cost reduction represents the business model closest to rural farming. However, also farms located in agglomerations' peri-urban fringes use this low-cost approach for profitability, and in the urban context, specific expressions have emerged. Commons are specialisation in high-value crops (horticulture) and methods to reduce costs, like using available and cheap urban surplus resources (heat, sewage water, biomass) (Pölling *et al.,* 2015).

5.6.4. The business model: sharing economy model

Lately initiatives based on 'sharing economy' (or 'the commons') increasingly gain importance as an expression of the new economy. Resources required to run urban agriculture in the form of a shared economy model, e.g. Community Supported Agriculture, are jointly mobilised and managed: land, labour, credit, tools, machinery, network contacts and knowledge. The experience focuses on providing authentic and catchy memories by selling a story (experience) in addition to a product. Place-making and training or leisure activities are essential elements that in this model are combined with food production.

5.7. Analysis of current European Projects

5.7.1. Methods

The publications and projects were analysed regarding the potential contribution of the elements of urban farming systems to circular economy approach for a resourceful, resilient and sustainable city.

This study was based on the literature available from various bibliographic reference databases (namely Google Scholar, Research Gate, Web of Science, Scopus) and the work of CA17133 members. The systematic literature review process was applied to select the latest and the most relevant studies on this particular topic. Specific terms were used, like «nature-based solutions in cities and vegetable production» and synonyms for «urban agriculture», «urban farming», «closed circular systems», «business models». The article's relevance was discussed and grouped into three to six persons (authors) per groups, dealing with each topic related to urban agriculture as a keystone contribution towards securing sustainable and healthy development for cities in the future.

Defining all the terms, from urban agriculture to the contribution of elements of urban farming systems – specially developed for dense urban areas (e.g. underground, vertical and rooftop farming) – in a circular economy approach, helping to understand the status of a circular city based on project-database of COST Action CA17133. Two surveys were developed to the COST members concerning the: (1) projects participating in the COST Action; and (2) water sources, treatment, storage and irrigation systems. In the first survey we combined expertise in food systems governance (Moragues-Faus *et al*., 2017), innovative production systems and business models, food safety, food waste, water consumption, irrigation systems, knowledge transfer, education, participation, alternative protein sources for feed and urban-rural-nexus analysis. It was screened through the project-database and added peer-reviewed publications which we identified as key-articles for our field of research. It was also identified research gaps and extracted research questions which need to be answered to proceed into the design of a circular city. No quantitative information on current water sources, treatment, storage and operating irrigation system are available for current urban farming projects. To fill up this gap, the second survey was carried out within the 250 participants of the COST Action CA17133 Circular City, in February 2019 on water resources of urban farming research projects. (To find the nine questions, the list of surveyed research projects and their geographical distribution, please look into the supplemental material). The case *green roofs in Lisbon* with native species study of urban landscape area, allows enhancing water use and sustainability in Mediterranean conditions.

5.7.2. Circular Cities: A Survey of Project Participating in the COST Action CA17133

The relevant projects based on a keyword search through the COST Project collection are shown in Table 5. Fourteen keywords were selected based on the definitions of Food Systems (Table 1) definition and are listed on the table (see columns D to R). About our 14 words searched, several gaps where identified with significate absence: Food transportation and distribution, Food processing and transformation, Food storage, Consumption and Compost. Few references were found related to governance, consumers, citizens, and authorities. We analysed 13 projects (Table 5). However, some of them need to be seen as extremes. Project 9 (Pyrolysis of faecal wastes) is listed due to its potential to close the loop of the system.

Table 5. Relevant projects identified by searching project-database of the COST Action on Circular Cities and publications. The search keywords were: circular cities

No.	A **Project**	B **Website if applicable**	C **Location**
1	Integrating Edible City Solutions for social resilient and sustainably productive cities – EdiCitNet	https://cordis.europa.eu/project/rcn/216082/factsheet/en	Tygron and other world cities
2	Urban and Peri-Urban Agriculture for sustainable local development: The Multi-stakeholder Policy Action Planning as a tool for reconciling sectorial policies	http://bit.ly/UPAforSustainableDevelopmentMuiti-StakeholderPolicyAction	Portugal
3	CITYFOOD – Smart integrated multi-trophic city food production systems – water and energy-saving approach for global urbanisation (2018-2021)	https://www.igb-berlin.de/en/project/cityfood	Norway, Sweden, Germany, the Netherlands, Brazil and the USA
4	Continuous Productive Urban Landscape: Designing urban agriculture for sustainable cities	http://www.foodurbanism.org/cpuls-continuous-productive-urban-landscapes/	Worldwide (sustainable urban design concept)
5	GEOFOOD (2018-2021)	https://geofoodproject.eu/	Iceland, Slovenia and the Netherlands
6	Living from the Earth – OTKA 116219 and OTKA 100682 (2016-2019) dealing with rural-urban divide and to make rural life attractive in Hungary, the changing role of the local small-scale agri-food production.	*https://www.aur.edu*	Hungary
7	NACHWUCHS – Nachhaltiges Agri-Urbanes zusammenWachsen (Sustainable AgriUrban Growth)	https://urbact.eu/agri-urban	Germany
8	Plattform «Produktive Stadt» [Platform «Productive City»]	http://blogs.brighton.ac.uk/pulr/2019/06/10/platform-productive-city-holds-its-2nd-participatory-workshop-germany/	Berlin (Germany)
9	Pyrolysis of faecal wastes	https://www.zhaw.ch/de/lsfm/institute-zentren/iunr/ecological-engineering/oekotechnologie/biochar-sanitation/	Waedenswil (Switzerland)
10	Productive Green Infrastructure for post-industrial urban regeneration (proGIreg)	http://www.progireg.eu/	Aachen (Germany)
11	Urban Allotment Gardens in European Cities: Future, Challenges and Lessons Learned	https://www.cost.eu/actions/TU1201	Riga (Latvia)
12	Characterisation of nutrient recycling processes of a model aquaponic system	https://www.zhaw.ch/de/lsfm/institute-zentren/iunr/ecological-engineering/oekotechnologie/aquaponic/	Waedenswil (Switzerland)
13	The smart and sustainable city district of the future	https://www.balticurbanlab.eu/goodpractices/hiedanranta-smart-and-sustainable-city-district-future-tampere	Häme (Finland)

Table 6. The goals of relevant projects identified by searching project-database of the COST Action on Circular Cities and publications. The numbers 1-13 denote the projects listed in Table 5.

	Project number												
Topic	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Stakeholders	x	x	x	x				x			x		
Food	x	x	x	x	x	x	x	x	x		x	x	**no**
Production	x		x	x		x	x	x	x	x			
Transportation / Distribution				x									
Storage				x									
Processing / Transformation				x									
Food Policy(-ies)		x	x	x		x							
Food System	x	x	x	x	x								
Governance / Authorities				x				x			x		
Consumers / Citizens	x	x		x				x					
Farmers			x	x									
Urban Farming						x	x					x	
Compost				x									
Circular city				x									x

The research areas addressed were: food policies, food systems, stakeholders engagement and awareness, urban and peri-urban agriculture for sustainable local development.

The survey includes also answers from COST members on the following questions:

(1) What are the critical questions from a members point of view?
(2) Critical points (gaps) enabling the contribution of urban farming to circular cities?
(3) Why is the understanding of urban farming within the food system critical to circular cities?
(4) Why the understanding of urban farming within the food system is a critical shift from linear cities to circular cities?

The topics presented in the thirteen projects were (Table 6): stakeholders, food, production, transportation and distribution, storage, processing and transformation, food policy(-ies), food system, governance and authorities, consumers and citizens, farmers, urban farming, compost and the circular city. Most projects covered topics related to food (11 out of 13), production (8 out of 13) and stakeholders (6 out of 13).

5.7.3. Water sources, treatment, storage and irrigation systems

The survey yielded 22 research projects, which geographically covered most of Europe. Water sources used by the projects were very diverse (Figure 3).

Interestingly tap water, as the only water source was used by only 23% of the projects, while most projects (45%) used a mixture of sources. The use of wastewater, greywater or stored rainwater was rare – one project relied to 100% on natural rain.

Regarding prior water treatment, 59% of the projects did not use any treatment of their water. The remaining used a variety of treatments including mechanical filters, plant-based, bio-reactor, sedimentation or disinfection systems. Only two of the ten hydroponic systems used greywater as a source.

The survey showed that (i) rainwater management or reuse infrastructures are often not readily in place to be used for urban agriculture projects, (ii) farming projects rely heavily on tap water and, (iii) circular usage of water is not yet common except in the hydroponic projects.

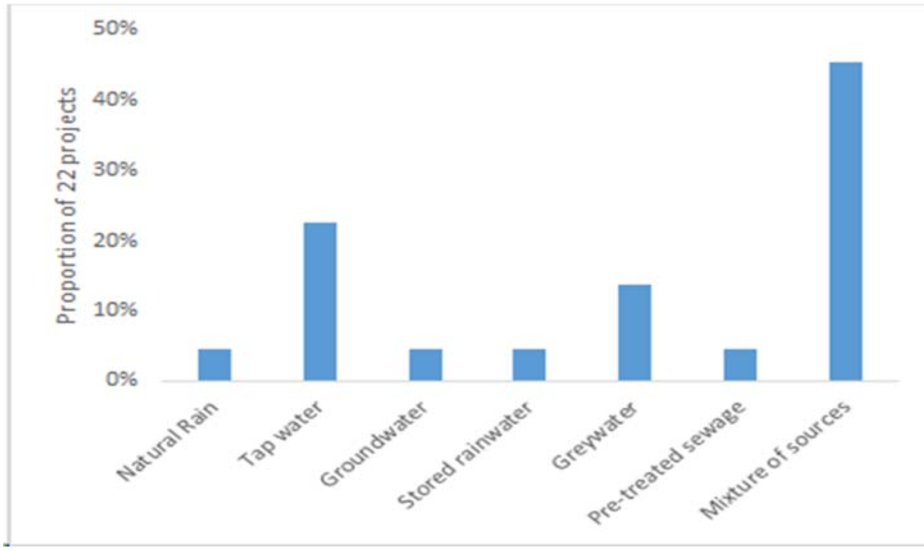

Figure 3. Sources of water supply for 22 recent urban agriculture research projects participating in the COST Action CA17133, February 2019.

5.8. Conclusions

The development of future cities is now approaching into smart and sustainable cities with a global understanding of how vital food production, supporting the circular economy, is. In 2050 about 50% of all people on earth are living in cities and will need clean water, food, energy, social space, meeting points, relax areas and knowledge pools.

5.8.1. Land use and planning

It is visible that municipalities around the world are beginning to consider food issues in their city planning proactively, most evident perhaps in the Food Policy Pact signed by more than 180 cities since its foundation in 2015 during the Milan World Expo. This rapid development has followed the mainly practice-based, citizen-led experiences with urban agriculture that emerged, as a conscious movement, in cities and at their edges for nearly 20 years. It is now of great importance to integrate urban food production and other food system activities into urban planning, thereby linking sustainable food provision and circular resource processes to infrastructural productive urban landscape development.

5.8.2. Water systems

Assessment of underlying spatial and temporal variability in water use decisions at a landscape scale regarding the water demand and irrigation water requirements in response to climate change and different urban farming location. Some projects (e.g. URBAN GreenUP; NativeScapeGR, Nature4Cities, CITYFOOD) focus on mitigation the effects and risks of climate change and improving the water management cities. Other projects contribute to a better understanding of ecosystem services through evaluation and mapping the urban environments(TUNESinURB, Nedkov *et al.*, 2017).

A better understanding how irrigation is used in the urban farming is needed to reduce pressures on limited freshwater resources, based on the knowledge how to use it efficiently based on economics, yield, environmental and social issues, aesthetics and safety for human health criteria. Assessment of underlying spatial and temporal variability in water use decisions at a landscape scale regarding the water demand and irrigation water requirements in response to climate change and different urban farming location.

What appears to be missing in most projects are concepts and experiences of water storage, rainwater harvesting and optimised usage of water with state-of-the-art irrigation systems. Very few long-term experiences exist at the moment for combining urban agriculture and any wastewater usage – as would fit within the concept of the circular city. As many current projects are using hydroponic systems, more research into a combination of hydroponic systems and wastewater reuse could be beneficial.

5.8.3. Air pollution

The economic growth, industrialisation and urbanisation has caused increased concentrations of pollutants such as ozone (O_3), nitrous oxides (NOx), sulphur dioxide (SO_2) and suspended particulate matter (SPM) in urban areas. These gases can cause significant damage to crops.

Suspended particulate matter has the most significant effect on crop yields and the quality of the crops. Several studies ascertained the correlation between the atmospheric pollutant deposition originating from traffic emissions (e.g. Cd, Cu, Cr, Ni, Pb and Zn) and the concentration of heavy metals in the vegetation and soil samples. Therefore it is necessary to assess thze suitability of produce grown near pollution sources for human consumption and also identify causal links between a specific pollutant and damage to crops.

5.8.4. Education and knowledge transfer

Combined circular food systems – aquaculture and plant production together in the same system – are entirely new in the perspective of food production techniques and can also be implemented widely in education and knowledge transfer (Junge *et al.,* 2019). In Norway researchers have focused on the development of recirculating aquaculture systems (RAS) during the past 30 years, and the production of the most salmonids fingerlings grow in land-based RAS. In NIBIO Landvik, an aquaponics facility is operated with salmonids (brown *Salmo trutta*, rainbow trout *Oncorhynchus mykiss* and a relict salmon species called "bleke" *Salmo salar* (Barlaup, 2011), together with a wide range of plant species, such as wild herbs, Asian greens, edible flowers, leafy plants and several lettuce varieties (Skar *et al.*, 2015). The system is used for research and education, and works as a showcase for an innovative approach to a more sustainable food production. The latest development is to apply the system into prisons, to creat jobs, building skills and build prisoners social acceptance in city communities by producing local and healthy food to the surrounding community (Skar 2018). Together with the system in Norway, further aquaponic systems were constructed for educational and knowledge transfer purposes, e.g. within the CITYFOOD project in Brazil and Germany and within the AQU@TEACH project in the United Kingdom, Slovenia, Spain and Switzerland. These so-called 'living labs' are serving as perceptible demonstration sites and are a central part of a diverse communication and dissemination agenda.

5.8.5. Knowledge gaps and further research question in urban agriculture

Consolidating the current knowledge on urban agriculture in green urban systems is needed. More knowledge is needed on multifunctionality and the relation to green infrastructure and food-productive urban landscapes, circular city debates and discussions of the possible adverse effect of air pollution on urban agriculture products' quality. Improved sustainability in the cities by integrating with buildings and waste conversion sites.

To encourage more holistic solutions to the problem, we present a comprehensive overview of European projects and examples which consider circular city approaches on urban farming. .Examples of solutions from our expertise and database COST Action is found here: http://www.circular-city.eu/images/pdf_download/Proceedings_COST_WS_13-15Feb.pdf

Due to the mainstreamed globalisation of urban food systems, the entire production and marketing schemes have shifted to comfort the needs of globalised value chains. Changes like these in the built environment and the socio-cultural practice create path dependencies. A significant gap of research on what a change in food production, -processing, -distribution and consumption can and will do to the cities, especially in the area of transportation/logistics, green infrastructure, resource streams and all the physical requirements on which they are based on (streets, shops, pipes, wires, channels and more). We also identified a gap in food governance research and realised an almost complete absence of the social dimension meaning the analysis of socio-cultural patterns and practices in the food preparation and consumption.

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6. WG5 review paper

Transformation Tools Enabling the Implementation of Nature-based Solutions for Creating a Resourceful Circular City

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Abstract

The linear pattern of production-consumption-disposal of cities around the world will continue to increase the emission of pollutants and stocks of waste, as well as to impact on the irreversible deterioration of non-renewable stocks of raw materials. A transition towards a circular pattern proposed by the concept of "Circular Cities" is gaining momentum. As part of this urban transition, the emergent use of Nature-based Solutions (NBS) intends to shift public opinion and utilize technology to mitigate the urban environmental impact. In this paper, an analysis of the current research and practical investments for implementing NBS under the umbrella of Circular Cities is conducted. A combined appraisal of the latest literature and a survey of on-going and completed National-European research and development projects provides an overview of the current enabling tools, methodologies, and initiatives for public engagement. It also identifies and describes the links between facilitators and barriers with respect to existing policies and regulations, public awareness and engagement, and scientific and technological instruments. The paper concludes introducing the most promising methods, physical and digital technologies that may lead the way to Sustainable Circular Cities. The results of this research provide useful insight for citizens, scientists, practitioners, investors, policy makers, and strategists to channel efforts on switching from a linear to a circular thinking for the future of cities.

Keywords

Nature-based Solutions, Circular Cities, Policies and Regulations, Stakeholders' Awareness and Engagement, Assessment Methods

Abbreviations

NBS:	Nature-based Solutions	IO:	Input-Output
CE:	Circular Economy	S-LCA:	Social Life Cycle Assessment
GI	Green Infrastructure	ES:	Ecosystem Services
ICT:	Information and Communication Technology	MAES:	Mapping and Assessment of Ecosystems and their Services
DSS:	Decision Support Systems	NW:	Networking
KESI:	Key Environmental and Socio-Economic Indicators	RIA:	Research and Innovation Action
LCA:	Life Cycle Assessment	IA:	Innovation Action
LCC:	Life Cycle Costing	CSA:	Coordination and Support Action
MFA:	Material Flow Analysis	FET:	Future and Emerging Technologies
CBA:	Cost Benefit Analysis	II:	Implementation and Integration
PD:	Participatory Design	TRLs:	Technology Readiness Levels
UM:	Urban Metabolism	WG:	Working Group
HHA:	Harvest to Harvest Approach	SDGs:	Sustainable Development Goals
SS:	Self-Sufficiency	R&I:	Research and Innovation

6.1. Introduction

Cities are complex systems under continuous evolution, whose internal dynamics and process interactions generate impacts on the population's health, socio-economic well-being, and the environment (Alberti 2008; Pickett et al. 2008). Nowadays these impacts are mainly driven by a "linear" behavior according to which exploitable resources are transported to the cities to provide the necessities of urban consumption and waste dynamics. The patterns of acquisition, consumption and the subsequent waste disposal of resources pose environmental and socio-economic implications. These patterns may also cause irreversible deteriorations of non-renewable stocks of raw materials and huge waste discharged in the outflow of the urban system (Brunner & Rechberger 2016). The concept of "circularity" is, therefore, gaining popularity among urban planners and decision-makers (Petit-Boix & Leipold 2018; Prendeville et al. 2018; Williams 2019; Zeller et al. 2019) to counter the imbalances caused by unsustainable linear practices. The effect of consuming diminishing raw materials at a faster rate than the ability of nature to restore is a matter of serious global concern.

Concurrently, the emergent concept of Nature-based Solutions (NBS) promotes the circular use of resources making use of closed nutrient, water, and energy cycles by reusing waste rather than discarding it (EC 2015). In urban areas, NBS could reinforce economic growth, which is highly dependent on the quantity and quality of natural resources, as well as on their availability (González-Val & Pueyo 2019), by promoting the sustainable use of natural resources and by harnessing natural processes (Connor 2015). The enhanced natural capital, as well as the efficient use of resources (i.e. energy and materials), facilitated by working with nature, would further build on the circular economy (CE) (UN 2018). Since CE initiatives at urban scale aim at transforming cities into sustainable and circular systems (Petit-Boix & Leipold 2018), NBS following the concept of CE as an intermediate link, can be seen as enablers to the transition from linear to Circular Cities. In this paper, we refer to NBS as defined in (Langergraber et al. 2019 submitted).

Traditionally, cities have been shaped by institutions (local, regional or national) to comply with regulations, while fostering socio-economic development. Current urban policies, legislation and regulations are generally written in and for a linear economy thus, they may (unintentionally) hinder the transition to a CE. According to (Stewart et al. 2016), policies and regulations can hamper CE by providing: (i) unclear or fuzzy messages, (ii) a complex system of changing regulations (e.g. multiple sectorial and interacting regulations on water, energy, waste, environment impact assessment), (iii) low pressure and a lack of control, and (iv) a limited space for innovation. Additionally, NBS are still poorly addressed by current policies and regulations related to CE. This may be due to the fact that NBS is a relatively novel concept in dealing with the challenges faced by society (i.e. societal challenges), and therefore, still searching for its place under different policies and regulations. NBS aims to address challenges associated with climate resilience, health and well-being in urban areas (IUCN 2012; Cohen-Schacham et al. 2016), integrating established ecosystem-based approaches, such as biodiversity, ecosystem services (ES), green infrastructure (GI) etc., and aiming in broadening them, in order to holistically tackle issues of environmental, economic and social nature in building resilience (Raymond et al. 2017). Within European Research and Innovation (R&I) programmes, e.g. 'Horizon 2020', NBS extend the aforementioned approaches involving biodiversity and ecosystem services aligned with goals of innovation for growth and job creation (European Commission 2015c) and work towards sustainable societal development (Maes & Jacobs 2017; Nesshöver et al. 2017). Therefore, due to NBS systemic nature there are inherent difficulties in integrating such a complex concept in policies and regulations (Niță et al. 2017). Unsurprisingly, supporting frameworks for NBS are provided by other instruments, such as the EU Green infrastructure strategy and the biodiversity strategy.

However, policies and legal frameworks can also accelerate the transition towards Circular Cities supporting solutions, such as NBS. Such an approach appears at the EU level since the Paris agreement with a set of EU strategies and policy papers connecting sectorial regulations and initiating a revision of existing Directives when further coherency is necessary. Thus, the EU Circular Economy package, launched in 2015 with an action plan composed of 54 items, is presented as a tool to foster the transition and encompass most of the barriers. Two key instruments are foreseen by the EC report on the implementation of the Circular Economy Action Plan (COM 2019): (i) Investments in innovation and in adapting the industrial base; with R&I (H2020), Environment (LIFE) programmes, Cohesion Policy or financing facilities. To overcome the regulation limits, pilot innovation deals have been introduced in 2016 and should be extended. (ii) Strong stakeholders' engagement to ensure co-design and social acceptance of solutions.

In this regard, stakeholders play a central role in supporting the transition from linear to circular pathways in cities. The long-term viability and durability, the extent of scalability for the adoption and implementation of actions, projects, and/or solutions, as well as the diffusion of good practices are perceived as the key in achieving and maintaining this transition (Kabisch et al. 2016). The involvement and collaboration of public, private and civil actors in the governance of NBS – enabling Circular Cities – can reduce barriers to NBS adoption on a wider scale of application (Frantzeskaki et al. 2014; Kabisch et al. 2016). The partnering of different actors can moreover improve the circulation of knowledge regarding NBS and Circular Cities (Ugolini et al. 2015). Citizens' participation and involvement can further facilitate the communication of information on NBS and their diffusion by the community (Kabisch et al. 2016). In this context, the use of participatory evaluation can be seen as a way to respect the legitimacy of different views on NBS quality, as well as to apply multiple perspectives provided by the different stakeholders (Nesshöver et al. 2017).

Another issue related to the relatively new concepts of NBS and Circular Cities is identified in the persisting challenges of the costs and benefits of circularity methods in cities (Raymond et al. 2017). Although the costs of the shift are tangible and measurable, the burden of proof on the short-term benefits of NBS is still on the proponents. Assuming that the long term (e.g. resilience and well-being) impact is understandable by stakeholders, the intangible short-term benefits are more difficult to convey. It seems that one of the major shortcomings is the lack of holistic and widely accepted methodology and/or framework to assess the circularity potential of such systems into the bargain, as argued by (Kabisch et al. 2016). There is a need for reaching consensus on the individual instruments and tools (methods, indicators, models, databases, etc.) capable of comparing linearity against circularity. The aim is to offer a roadmap and the tools to converge methodologies and integrated functionalities to estimate the costs and benefits of circular against existing linear solutions. The roadmap paves the way and the tools provide the means to achieve the goal. The proposed toolbox would contain methods and models to quantify a set of Key Environmental and Socio-Economic Indicators (KESI) integrated by Information and Communication Technology (ICT) and in the form of software applications to aid in decision making (i.e. Decision Support Systems). These platforms will become the instruments to compare circular against linear scenarios, and demonstrate short-term and long-term tangible and intangible benefits of modern Circular Cities. Such objective measurements will become the drivers of public awareness/education and investment.

The goal of this review paper - developed within the framework of the COST Action Circular City (CA17133 2018) – is threefold: i) to identify and group specific tools and methods that are used to assess NBS for implementing and improving circularity in cities, ii) to identify means of society and stakeholders' engagement and awareness, and iii) to identify barriers and facilitators within current policies and regulations in order to promote and enable the implementation of NBS for improving future city transitions. The identification of current gaps, needs and opportunities will help to transfer research results into the market and to upscale existing pilot applications into the ground of concrete decision-making for NBS.

6.2. Methodology

To identify the current gaps and opportunities regarding the transformation tools enabling the implementation of NBS for creating Circular Cities as stated in the introduction, an analysis was performed that includes: (i) the interconnections between policies and regulations, engagement and participation of stakeholders, and tools and assessment methodologies, during the implementation of NBS (section 3); (ii) a literature review focusing on the up-to-date scientific research (section 4); and (iii) a survey of projects related to NBS for creating Circular Cities that would enable the comparison between scientific research and practical applications (section 5). The paper focuses on the survey of National-European research and development projects, which sets a delimitation of this study with regards to NBS contributions to sustainable research and development in European context.

6.2.1. Literature Review Approach

The conducted literature review (section 4) is divided in 3 subsections, namely *4.1 Policy and Regulations*, *4.2 Stakeholders Engagement and Awareness*, and *4.3 Tools and Methods*. The review is based on peer-reviewed papers published in international scientific journals and on high-level policy documents. The identification of the relevant papers was conducted using related key words in the Science Direct and Scopus databases. High-level policy documents were chosen as the planning and implementation of NBS is supported by such documents.

The focus of the review is to: (i) identify current policies and regulations at EU level that should be conserved when implementing NBS for Circular Cities, as well as to understand the importance of the social, economic and environmental dimensions to be considered in and inform the policies (section 4.1);

identify the challenges related to public awareness and social acceptance, as well as to review methods that have been developed to increase the stakeholders engagement in NBS (section 4.2); and (iii) identify promising tools and methods that have been developed by researchers and can be used to assess the different dimensions (environmental, economic, and social) of the effectiveness of NBS (section 4.3).

6.2.2. Project Survey Approach

The members of this COST Action hold key knowledge on different aspects of NBS and Circular Cities and they participate in national, European and academic projects related to these subjects. Therefore, past and ongoing projects were reviewed and a meta-analysis of policies and regulations, stakeholders' awareness and participation, as well as the tools and methods assessing the technologies and systems was conducted.

Data from the projects were collected through a specially designed online questionnaire, which was carried out during March 2019. The main aim of the survey was to collect useful information on the different projects in order to compare and identify the gaps between scientific literature and practical applications.

The questions included in the questionnaire were divided in 4 main categories. The first category included questions related to general information of the projects, such as:

- Project title;
- Project type – the projects are divided by: i) Networking (NW), ii) Research and Innovation Action (RIA) and Innovation Action (IA), iii) Coordination and Support Action (CSA), iv) Future and Emerging Technologies (FET), and v) Implementation and Integration (II);

- Project stage – from recently started to completed;
- NBS focus – four categories, corresponding to the working groups (WG) of this COST Action, were specified: Built Environment (WG1), Urban Water (WG2), Resource Recovery (WG3), and Urban Farming (WG4);
- Implementation level – i.e. conceptual, experimental, on-ground, and capitalization projects;
- Application scale – *micro* (technology, material, energy, etc.), *meso* (building, neighbourhood, landscape, etc.), and *macro* (district, city, region, etc.);
- TRL of the different technologies – the scale ranges from 1 to 9 with TRL 1: basic principles observed and reported, and TRL 9: system ready for full-scale deployment;
- SRL of the project – the scale ranges from 1 to 9 with SRL 1: identifying problem and identifying societal readiness, and SRL 9: actual project solution(s) proven in relevant environment.

The second category was related to the methods that were used for the assessment of the NBS and the ICT tools that were either developed or used in the projects. The third category was focused on the type of policies and regulations that were considered in the project, the main barriers that were identified in the projects, as well as supporting measures (of policy or regulations) to ensure the success of the project. Finally, the fourth category was related to the type of the stakeholders involved in the project, the barriers for the implementation of project activities related to stakeholder's awareness and engagement, the types of public participation tools and techniques used in the project and the level of stakeholders' engagement in the project.

A total number of 47 relevant research projects were studied (the list of the reviewed projects can be found in Appendix 1) and the results of the conducted survey are presented in section 5.

6.3. The Scope of Nature-based Solutions in Circular Cities

There are four main steps for the implementation of NBS in creating Circular Cities: i) planning, ii) design, assessment and, iv) communication of results. As illustrated in Figure 1, it is important to close the circular process starting a new planification based on the information provided in the communication of previous implementations. Tools are used in all of the four steps in order to enhance the dialogue among the different actors, as well as the engagement and participation of the stakeholders to induce sustainable changes and assess the environmental, economic, and social improvement of the cities, and finally to inform the policy making.

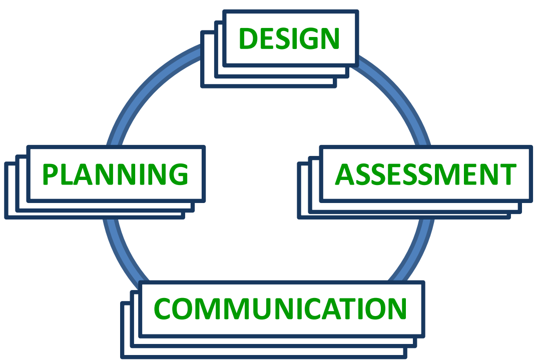

Figure 4: Circular process for the implementation of NBS in Circular Cities

The **planning** phase requires information about the regulations that must be fulfilled and the city where the NBS will be implemented aiming at becoming a circular city (specific problems to be solved, citizens awareness and perception about the problem, characteristics of the city including potential sites to implement the NBS, possible/alternative NBS to implement, and similar case studies and demo sites implemented around the world). The typical tools used for planning include decision support systems, multi-criteria decision analysis, repositories of case studies (literature or web-based), models and databases with information about the former value of the indicators that will be used for the assessment, exploratory/visualization tools to determine the characteristics of the city/sites (e.g. aerial images, land space, green coverage, etc.), and participatory digital platforms. Most of these tools were applied in literature case studies, but they still have to overcome some serious challenges before reaching the market and being fully applied for decision-makers (McIntosh et al. 2011; Poch et al. 2017).

The **design** and implementation requires the use of engineering design knowledge, process models and specific software. Involving general stakeholders and the specific neighbourhood citizens to co-design the NBS becomes crucial for the acceptance and engagement of the society.

The **assessment** phase includes process performance monitoring (sensors, instrumentation, automation, control) and any measurement or assessment of the impacts (beneficial or detrimental) of the implemented NBS (by using methodologies, such as Life Cycle Assessment - LCA, Life Cycle Costing - LCC, Cost Benefit Analysis – CBA etc.). Moreover, specific software, web-based questionnaires and apps (e.g. citizen science, where the citizens become the "sensors" for monitoring both the performance and the impact of the NBS) are usually used for this purpose.

Finally, the **communication** phase includes the dissemination to citizens and stakeholders (for their real engagement and in order to increase social perception about the new services of the Circular Cities) and any potential exploitation activities. Efficient communication should make the planning a living process, while revised planning based on communication starts the whole implementation cycle again. The most typical tools for communication are social media and web-based platforms that include repository databases, case studies, user-friendly Decision Support Systems (DSS), simulations, and participatory platforms. This step is the key to provide information to new cities that want to become resourceful and circular. Excellent science needs effective communication and dissemination. Bringing research and its outcomes to the attention of non-scientific audiences, scientific peers, potential business partners or policymakers fosters collaboration and innovation. Strategic communication and dissemination will help to explain the wider societal relevance of science, build support for future research and innovation funding, ensure uptake of results within the scientific community, and open up potential business opportunities for novel products or services.

6.4. Overview

6.4.1. Policy and Regulations

Regulation and governance arrangements can be considered as tools supporting policy strategies. Figure 2 presents the different facets of these three pillars, i.e. policy, regulation and governance, which are necessary for the long-term stability of NBS for circular city initiatives.

The governance of NBS emerges as a complex phenomenon, involving multiple social and political actors, premises and visions. Defining the appropriate mix between the involvement of state, local authorities, private sector and grassroots movements remains challenging, in particular in terms of cost sharing and long-term sustainability. Participatory approaches with multiple stakeholders' impacts evaluation and a strong civil society engagement appears as a successful approach governance (Naturvation 2017).

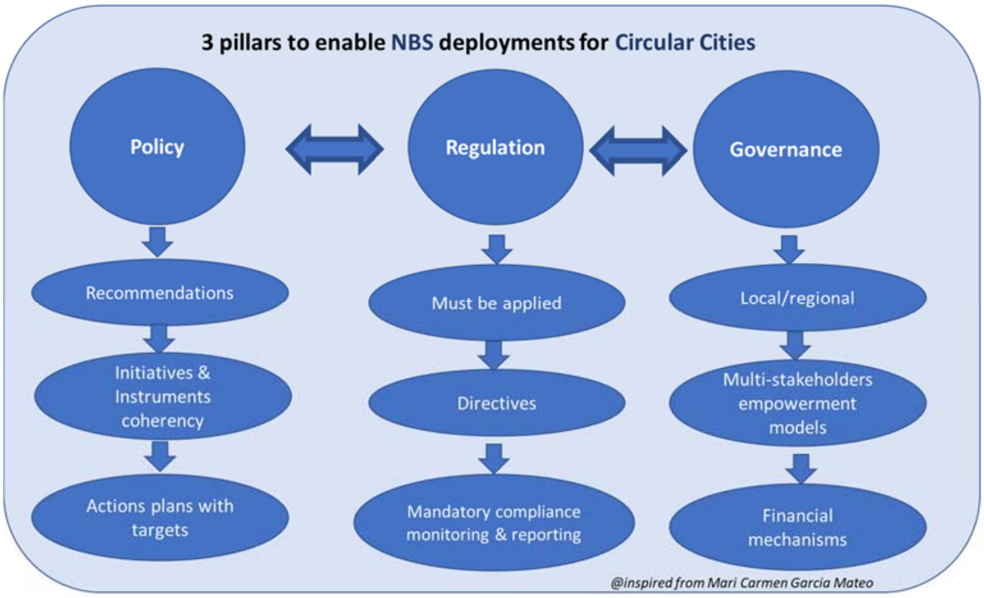

Figure 5: 3 pillars to enable NBS deployments for Circular Cities

In the context of this paper, a state-of-the-art analysis of EU regulations and policies is conducted. An inventory of a wide range of EU instruments to be conserved when implementing NBS for Circular Cities is presented in Table 1. The different EU regulations are categorized based on their content and they are linked relevantly to the four different challenges addressed by NBS, as presented in (Langergraber et al. 2019 submitted). Due to its wide diversity, the local dimension requires further research, in particular considering the relationships between Circular Cities and their surrounding environment, such as the river basin when considering aquatic ecosystems or the whole region for secondary products created from urban circular economy (e.g. fertilisers derived from sludge or organic waste).

Regulations are often seen as barriers for innovation, but they are also providing an enabling environment for new product development and marketing.

UN and ISO non-binding frameworks support NBS implementation for Circular Cities. For example, the frameworks on "treated wastewater for irrigation", "drinking water quality guidelines" and "Sustainable Development Goals" (SDGs) are worth mentioning. Often it is challenging translating such strategic and visionary frameworks at the operational level and in local contexts, especially in areas with weak planning and regulation systems (i.e. some areas in Central and Eastern Europe). Moreover, even the EU directives contain many non-legally binding articles related to water reuse. For example, Article 12 of the UWWD suggests that "Treated wastewater shall be reused whenever appropriate. Disposal routes shall minimize the adverse effects on the environment". However, it is the member states that decide if and where it is appropriate. After years of discussion, Water reuse standards are being accepted at EU level, but they are only related to reuse in agriculture. Other uses (e.g. in urban areas) remain unregulated at EU level.

The EU regulations listed in Table 1 show that the need to protect natural capital and value ES are recognised as being crucial to progress towards the sustainable development goals. A notable example is represented by the European Union actions towards sustainable growth for Europe 2020 and EU Biodiversity (COM 2011) and Green Infrastructure (COM 2013) strategies. Furthermore, the European Union Thematic Strategy on the Urban Environment (COM 2005) recognizes that it is in urban areas that the environmental, economic and social dimensions of the EU Sustainable Development Strategy come together most strongly (Raymond et al. 2017). Therefore, NBS are directly relevant to several policy areas and through their systemic nature they interact with many others (land use, planning etc.).

Table 1: EU policies and regulations for the implementation of NBS in Circular Cities

<table>
<tr><th>EU policies / strategies</th><th colspan="2">EU regulations</th></tr>
<tr><td rowspan="6">▪ Circular Economy Package: Action Plan and Monitoring Framework
▪ Green Infrastructure Strategy
▪ Bio-economy strategy
▪ Regional Development and Cohesion Policy
▪ Biodiversity strategy
▪ Common Agricultural Policy (CAP)
▪ Framework Programme for Research and Innovation
▪ Environment Action Programmes</td><td>Resource recovery</td><td>Waste Framework Directive (2008/98/EC)</td></tr>
<tr><td>Built environment</td><td>Energy performance of buildings Directive (2010/31/EU)
Energy efficiency Directive (2012/27/EU)</td></tr>
<tr><td>Built environment
Water
Resource recovery
Urban farming</td><td>Environmental Impact Assessment (EIA)</td></tr>
<tr><td>Resource recovery
Urban farming</td><td>Sewage Sludge Directive (86/278/EEC)</td></tr>
<tr><td>Resource recovery
Urban farming</td><td>Fertilisers Regulation (EC) No 2003/2003</td></tr>
<tr><td>Water
Resource recovery
Urban farming</td><td>Water Framework Directive (2000/60/EC)
Groundwater Directive (2006/118/EC)
Drinking Water Directive (98/83/EC), revised on 1 Feb 2018
Urban Waste Water Directive (91/271/EEC)
Minimum requirements for water reuse COM (2018) 337 (2018/0169 (COD))</td></tr>
</table>

The EU policies/strategies reported in Table 1 do also suggest that sustainability assessment has recently become an important issue for policy and decision makers in Europe due to a recognized requirement of balance between environmental, economic and social policies. The interlink between these policies require a simultaneous consideration of the intersection between environment, economy and society of sustainable development to have a better environment, economic growth (ideally decoupled from resources exploitation) and welfare of society without compromising the wealth of future generations as indicated in Brundtland Commission definition of sustainable development (WCED Brundtland Commission 1987). There exists an inherent risk of new technology implementations on the balance of policies related to the three pillars of sustainability.

Although the social dimension to sustainability is widely recognized, performing a social assessment is difficult due to a lack of indicators that can be directly employed in technical analyses. Therefore, attention has been given to determination and quantification of social factors or the interaction of the social variables in a complex relationship. Without quantified and properly determined social factors, the impact of policies and technologies on the well-being of society and environment may not be a solid base for future policy strategies. Thus, the assessments of economic and environmental dimension without considering the social effects are insufficient (Carrera & Mack, 2010). The social acceptance of technology, renewable energy and environmental policies are progressively becoming more important for policy and decision makers worldwide aiming to design policies that reach attempted targets smoothly with community support. Therefore, social acceptance could be considered to be a promising factor for social assessment. As an emerging solution to environmental problems, NBS related projects or technologies are subject to social acceptance. There is a need to consider aspects of urban management, governance, biodiversity etc. within a society and integrate diverse systems of knowledge and values for NBS design and implementation in order to be socially comprehensible and acceptable to a range of stakeholders (Maes & Jacobs, 2017).

6.4.2. Stakeholders Engagement and Awareness

Public awareness and social acceptance of the NBS for Circular Cities is important for its proliferation and success in the future. Kabisch (Kabisch et al. 2016) identified that one of the major impediments on proliferation of NBS is the traditional structures of city departments and the "sectoral language", which traps knowledge into "sectoral silos"; or the so-called compartmentalization of professionals with different educational background and different objectives (Brink et al. 2016). Implementation of NBS requires cooperation across departments of the administration or between various actors with different, and sometimes, competing objectives. Therefore, there is an imperative need of an agreement on the societal values, based on which urban development will be planned and adopted. In order to be able to communicate and create impact, all stakeholders should refer to universal: (a) definitions of the key concepts, (b) values and valuing system, (c) metrics and indicators, (d) benchmarks and points of reference. Such an approach creates a common language and the foundations of the information and knowledge to be shared and customised for stakeholders (e.g. public, investor, regulator, and policy maker).

Provided the message can be conveyed appropriately, the next challenge is to assess the willingness of stakeholders to accept and adopt the solutions offered to them. In other words, what kind of short- and long-term benefits against the investments are made. This is especially relevant when the former is relatively immediate and the latter takes longer to be implemented.

Wüstenhagen, (Wüstenhagen et al. 2007) suggest three elements of social acceptance: socio-political, community and market acceptance. Note that, the convergence of socio-political, community and economic factors determines the *"willingness to accept"*. Socio-political acceptance can be enabled through regulatory frameworks and government standards (Beck & Martinot 2004).The benchmarks and measurable indicators of socio-political factors should provide the framework for firstly examining the procedural justice, which refers to decisions making with respect to the collective interests of all stakeholders (Walker 2009). The second indicator of socio-political factors of acceptance is the distributional justice. Social trust can be achieved by fair distribution of costs and benefits and equal rights of access to information by citizens and decision makers. Efforts are necessary to quantify socio-political acceptance, as this is one of the major components in order to achieve social acceptance (Rosso-Cerón & Kafarov 2015). In the case of NBS, even though a small but growing number of countries have adopted regulatory frameworks promoting them (WWAP 2018), in the majority of cases, a universal and precise legal framework for NBS and following procedures for stakeholder's awareness and engagement is still lacking and thus, limiting the outputs of the projects.

Community acceptance stands for local stakeholders' impression of the benefits that new NBS technologies or circularity initiatives bring to their respective communities. Normally, the methods for an objective examination of community acceptance, is the level engagement with disseminated information about projects and technologies (e.g. relevant subscription on social media, specialist magazines, local media …). Furthermore, active and voluntary engagement of the community with surveys, attending town hall meetings, focus groups are other modes of increasing awareness as well as gauging acceptance. Roddis, (Roddis et al. 2018) for example, focused on the community acceptance of onshore wind and solar farms implementation plans in Great Britain (for the years between 1990 and 2017), by composing a set of indicators.

Market acceptance mainly gauges consumers' utility towards paying or contributing to an initiative or product. Added to the consumers are the role of investors and the business-to-business relationships (e.g. value chains) and their perception of short and long term cost and benefit of resource allocation. Wüstenhagen (Wüstenhagen et al. 2007) for example, provide an insight to the attitudes of international companies towards different initiatives.

As the engagement of stakeholders in NBS to realize Circular Cities is widely understood and increasingly highlighted in the literature, some methods that have been developed to increase the stakeholders' engagement have been additionally reviewed. Design thinking is one of them, which deploys the typical design workshop setting for iteratively prototyping ideas and can be inscribed within the umbrella of Participatory Design (PD). PD aims at incorporating end-users as full participants in development processes. Mazé (Mazé 2007) compares PD to user-centered design, which draws on diverse means of studying, analyzing and incorporating user needs into product development. PD focuses on different means for bringing design processes, representations, and products to participation by stakeholders with diverse skills and expertise. In Scandinavia, Atelier (Binder et al. 2011) defines participatory design as an approach that attempts to involve end-users in the design process. The author characterizes DT similarly to Redström (Redström 2008) "use before use". Atelier's "design things" is inspired by Schön's reflective practitioner (Schön 1983) following an iterative design process through envisioning, prototyping, and experiencing. Through these phases, participants undergo emotional and cognitive experiences and they express themselves by engaging in practical action together, in a group. The inclusion of creativity can take different forms in different participatory approaches used today (Rizzo et al. 2015).

According to a recent study on Food Policy Councils (Bassarab et al. 2019) the most wide-spread strategies to raise stakeholder's engagement include encouraging community members to participate in actions realizing NBS, hosting public events and forums, surveying community members, distributing newsletters, developing specific community engagement strategies, or cross-promoting partner organizations' events. Time, lack of basic knowledge on NBS and lack of engagement plan are also decisive factors to achieve stakeholders' engagement on a high level.

6.4.3. Tools and Methods

According to EC (EC 2015), NBS can address one or multiple societal challenges in sustainable ways and simultaneously provide multiple co-benefits for health, the economy, society and the environment. Despite such strong belief, one can observe a severe lack of practical and targeted guidance for assessing the impacts of NBS within and across different societal challenges (Raymond et al. 2017). Previous studies have either (i) assessed the performance of NBS with regard to specific challenge areas, such as regulating urban surface runoff (Zölch et al. 2017); (ii) assessed the performance of NBS with regard to their multiple co-benefits and compared them to alternative solutions, e.g. the study of Liquete (Liquete et al. 2016); (iii) examined a set of indicators that can be used to measure the effectiveness of NBS addressing a specific societal challenge and the co-benefits, e.g. the studies of Kabisch (Kabisch et al. 2016) and Xing (Xing et al. 2017); or (iv) developed conceptual frameworks that still lack operationalization (e.g. Raymond et al. 2017; Calliari et al. 2019).

The same issue arises for CE initiatives realizing Circular Cities (i.e. lack of practical and targeted guidance for assessing circularity initiatives), as the available published data is insufficient to assess these strategies at the city-scale. On one hand, most of the cities' initiatives are accessible in the cities' web pages and databases, i.e. grey literature (e.g. Bastein 2016; Glasgow Chamber of Commerce 2016; Mairie de Paris 2017; Sack-Nielsen 2018). On the other hand, not all of the previous studies, assessing the environmental performance of CE strategies – published on peer-reviewed journal articles – have framed their assessment within the CE context (Petit-Boix & Leipold 2018).

In this work, a transdisciplinary approach – since circularity and sustainability concepts necessarily depend upon the interaction between the three spheres of society, economy and environment – has been undertaken to identify the tools and methods that have been used to assess NBS enabling circularity transitions from the literature. After the first classification of these tools and methods from the literature, the additional projects' survey – presented in section 4 – was used to identify the most common tools and methods that are actually used in projects. Therefore, this large set of instruments, potentially suitable to address many of the open transdisciplinary questions associated with the quantitative characterization of Circular Cities, was summarized into categories (as presented in Table 2).

The analysis of the tools and methods used in the projects indicates that there is an extensive diversity in the use of methods for the assessment of NBS; however, their application is mainly performed case specific without taking advantage of the complementary features that often those methods offer. This is the case, for example, for the majority of the methods emerging from the present survey, i.e. LCA and ES assessment with MAES. Their screening in the context of the selected projects suggests that more research efforts are needed to identify mutual strengths and integrate different modelling approaches, e.g. the cascade modelling framework (Potschin-Young et al. 2018), to address multiple challenges, such as the accounting for bundles of services at different spatial and temporal scales. Some recent literature focusing on the combination of LCA and ES methods, for example, fosters the alignment of existing ES classification systems to accepted life cycle inventories (LCIs), and the implementation of a consensual ES-LCA framework (Othoniel et al. 2016; Verones et al. 2017; Maia de Souza et al. 2018). At the same time, studies dealing with life cycle thinking combined with urban metabolism (UM) assessment and/or input-output (IO) analysis methods (e.g. Pincetl et al. 2012; Goldstein et al. 2013; Beloin-Saint-Pierre et al. 2017; Petit-Boix et al. 2017; Sohn, et al. 2018) confirm the findings of the present review, i.e. that both UM and IO based models can arguably benefit from the accommodation of bottom-up LCI technology knowledge, which considers micro-scale details, although this at the expenses of increased modelling complexity. Other attempt to use the complementary features of methods is hybridization of UM and LCA. While MFA-based approaches, such as UM, HHA, SS, measure material flows to/out of a city or system, which is useful for the quantification of the circularity potential, it lacks assessing the environmental impacts of these flows. Thus, hybridization with LCA fills up this gap and it was implemented in (Chester et al. 2012; Goldstein et al. 2013).

Table 2: Description of the most common tools and methods for NBS assessment

Name of Tool / Method	Description from Literature	Scope of Assessment		
		Enviromental	Social	Economic
Life Cycle Assessment **(LCA)**	"LCA addresses the environmental aspects and potential environmental impacts (e.g. use of resources and the environmental consequences of pollutant releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave)." (ISO 14040 2006)	x		
Life Cycle Costing **(LCC)**	"LCC is a technique that assesses costs over the life cycle of a product or a system." (Rödger et al. 2018)			x
Cost Benefit Analysis**(CBA)**	"CBA compares the gains and losses associated with an investment project (a road, railway line, port, urban expansion, etc.) or with a policy, e.g. the setting of an environmental standard." (Pearce 1998)	x	x	x
Material Flow Analysis**(MFA)**	"MFA methodology evaluates the flow of materials entering and leaving a system and their impact in the environment" (Rincon et al. 2013)	x		x
Urban Metabolism**(UM)**	"Modelthatquantifiesprocessesandallowsthemeasurementoffourmaincyclesorflows: Water, materials, energy and nutrients" (Kennedy et al. 2007; Pincetl et al. 2012)	x		
Harvest to Harvest Approach**(HHA)**	"Urban Harvesting reduces single source dependence by optimizing the demand and by harvesting local resources."(Wieleaker et al. 2018)	x		
Self-sufficiency**(SS)**	Self-sufficiency is achieved by reusing output as an input, (partially) covering the input demand. SSI can be used as a measure for the extent of self-sufficiency of a system(Wieleaker et al. 2018).	x		
Mapping and Assessment of Ecosystems and their Services **(MAES)**	''MAES is a conceptualframework that links socio-economic systems with ecosystems via the flow of ecosystem services and through thedrivers of change that affect ecosystems either as consequence of using the services or as indirect impacts dueto human activities in general.'' (Maes et al. 2013)	x	x	x
Social Life Cycle Assessment **(S-LCA)**	"A social and socio-economic Life Cycle Assessment (S-LCA) is a social impact (and potential impact)assessment technique that aims to assess the social and socio-economic aspects of products and theirpotential positive and negative impacts along their life cycle encompassing extraction and processing ofraw materials; manufacturing; distribution; use; re-use; maintenance; recycling; and final disposal." (Andrews et al. 2009)		x	

In this regard, the present analysis has further confirmed that it is worth adopting the main assets of LCA in the context of macro-scale assessments, e.g. the standardization criteria of the LCA method, the representativeness, transparency and completeness of the LCI databases, the necessary flexibility to host different types of flows in LCA models, not only physical but also monetary flows, etc. However, the isolated use of LCA and its family of methods (such as S-LCA, LCC, etc.) will always generate biases and a lack of consideration of the many landscape features, cultural diversity, and socio-economic attributes that characterize the cities as complex and dynamic systems. Therefore, a more top-down approach shall be undertaken to coupling LCA with other tools. As already highlighted by some works (e.g. Onat et al. 2017; Marvuglia et al. 2018; Beaussier et al. 2019), when combined with LCA tools, such as system dynamics, agent-based modeling etc., can allow to capture the multifaceted features of those systems, bringing to more comprehensive studies of the urban metabolism as a showcase to establish circular city models.

Additionally to the previously described assessment methodologies, a number of decision support tools has been used aiming to facilitate the NBS implementation in cities. Most of them focus on sustainable urban drainage, i.e. on integrating water and green infrastructure to achieve multiple benefits. To name a few, Urban BEATS (Bach et al. 2015) simulates the planning, design and implementation of water sensitive urban design infrastructure in urban environments. In addition the Adaptation Support Tool (Voskamp & Van de Ven 2015) facilitates the collaborative planning towards more resilient and attractive environment. E2STORMED is a comprehensive decision support tool that applies Multi-Criteria Analysis (Morales-Torres et al. 2016) and includes a catalogue of more than 20 types of drainage infrastructures. Radinja et al. (2019) have introduced a DSS that supports design and evaluation of blue-green infrastructure based on hydrology-hydraulic modelling.

6.5. Survey Results and Discussion

This section presents the results of the survey as described in section 2.2. It is important to underline the fact that most of the information extracted from the target projects is self-reported, while the projects come from various scientific fields, scale of enforcement or lines of financing. Therefore, the survey results put the basis for a broader analysis.

Figure 3 shows the general information about the surveyed projects, while results that specifically focus on Policy and Regulations, Stakeholders Engagement and Awareness, and Tools and Methods are presented in the following sub-sections.

Regarding the different project types – shown in Figure 3(a) – around 70% of the projects are self-identified as RIA and IA, indicating that there is a considerable amount of pilot projects that are actually implemented. The majority of the projects have low to medium Technology Readiness Levels (TRLs) indicating that the maturity of either the investigated topic (NBS and related applications) or the application of the method(s) still necessitates improvements and innovation. This may be explained by the fact that the concept of Circular Cities is quite recent, while the direct or indirect quantifiable, social/economical or ecological benefits captured by the implemented NBS projects are still quite unexplored (Marin and De Meulder 2018; Petit-Boix and Leipold 2018).

The second classification – related to the focus of NBS (Figure 3(b)) – results in an equal representation of all categories, which indicates that NBS for Circular Cities involve all sectors and disciplines in the urban development.

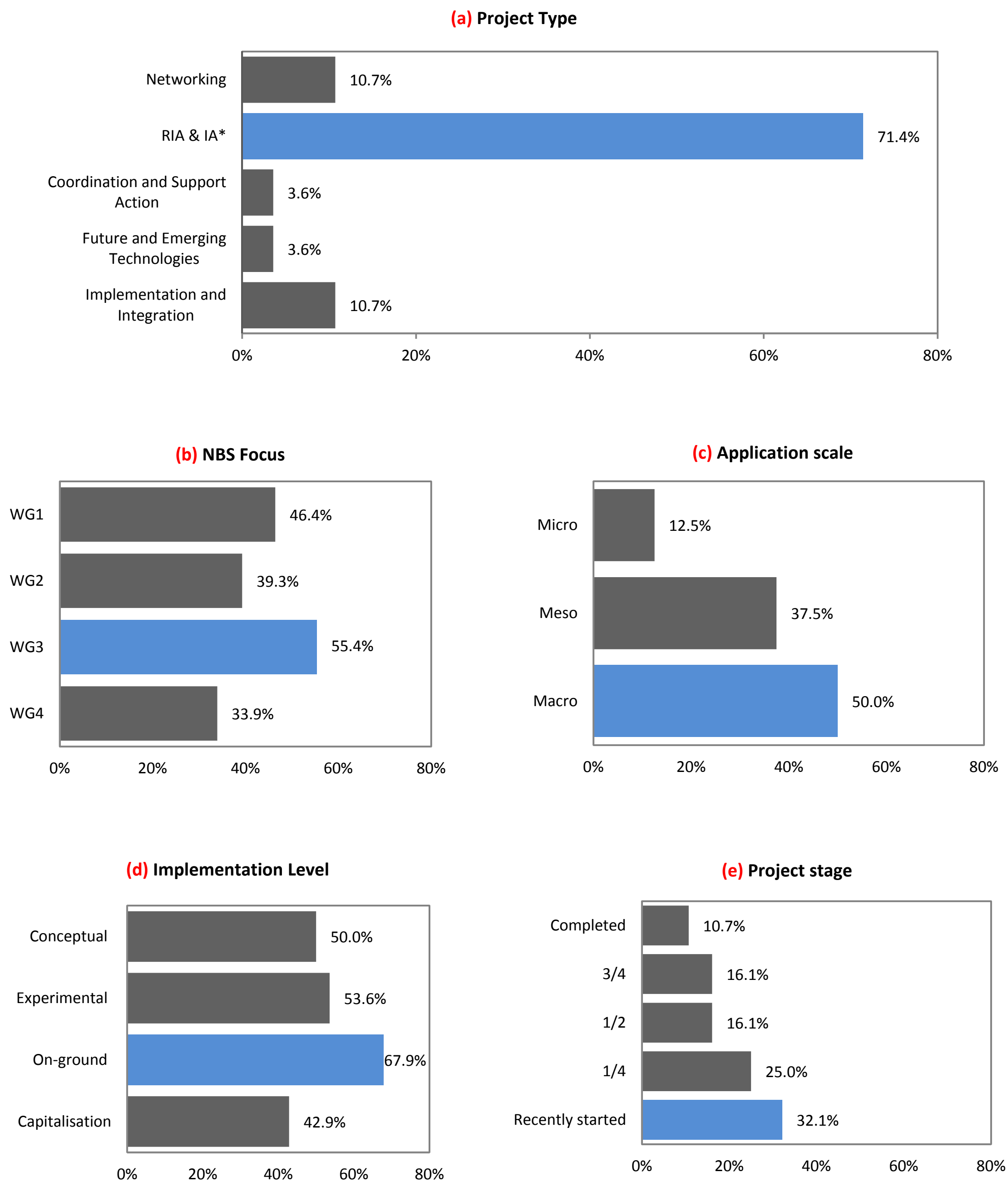

Figure 6: Categorization of the selected projects. (* RIA stands for Research and Innovation Action, IA stands for Innovation Action)

The results regarding the implementation level (Figure 3(d)) demonstrate that different levels of implementation exist within the same project. Interestingly, a large amount of projects (almost 68%) implemented their technologies on ground (real engineering practice), which indicates the intention to provide empirical verification of the NBS concept.

Furthermore, the respondents stated the current project stage, i.e. level of completion ranging from just started to completed, at the time of the survey (Figure 3 (e)). Out of the total of respondents, 10.7% of the projects are completed and 32.1% have started recently.

6.5.1. Policy and Regulations

To understand the barriers or drivers that policies and regulations pose in practice, the following analysis was conducted. Among the 47studied projects, 48% have considered European policies and regulations as the most important drivers or obligations for the project's implementation, followed by local regulations and governance (41%). Additionally, only 22% of the 47 projects undertook a policy/regulation review while, less than 10% have considered policy indicators for monitoring the success of their project.

Figure 4 shows the role of policy and regulation as drivers or barriers to NBS proliferation. Figure 4 further indicates that policy instruments, such as innovation, social, SDGs, and GI, are driving the changes while, more classical policies – linked to regulatory frameworks, such as water resources or environment – are considered as equally introducing drivers and barriers. It is worth noticing that agriculture and biodiversity policies and regulations are perceived as more limiting rather than enabling the development of NBS. This can be due to NBS being developed in a close connection to the urban environment and its searches for sustainability or resilience, therefore NBS still need adjustments in spaces where the main objectives are different: biodiversity conservation or food production.

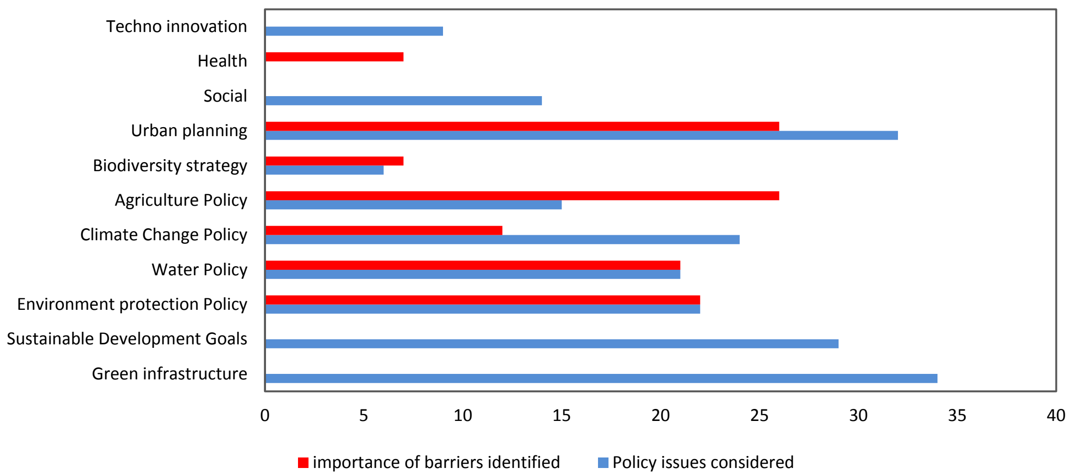

Figure 7: Policies and Regulations considered by projects and main barriers identified.

In addition to the survey conducted, Brink (Brink, et al. 2016) identifies the lack of space in dense urban areas, environmental and building permits, and the possible conflict of interests with other ecosystem services (such as drinking water production), which can determine the appearance of ecosystem disservices in some situations (Schaubroek, 2018), as additional barriers to the NBS implementation.

Policies can include the creation of supporting framework, requirement or incentive to foster the development, implementation and deployment of NBS in cities. Figure 5 presents the types of such supporting measures that the projects surveyed are considering as positively impacting their development. Most of these projects are science driven, so unsurprisingly research & innovation frameworks are considered first, followed by the political commitment and ownership. A suitable environment for market exploitation associated with financial incentives (grants and reduced taxes) is expected to boost NBS deployment in cities. Additionally, a long-term perspective of local governments on funding is necessary in order to create stability, decrease uncertainty for activities and enable voluntary action for a sustainable transition.

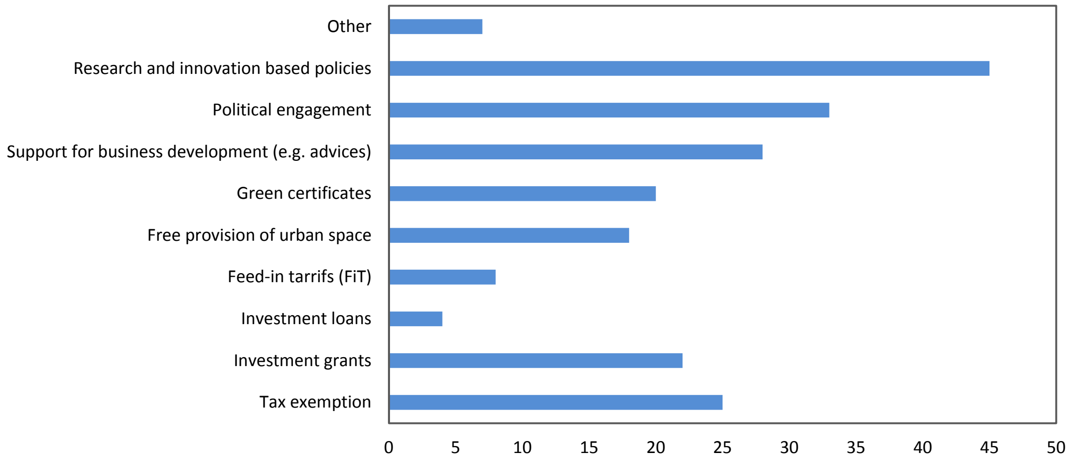

Figure 8: Supporting measures considered by projects

6.5.2. Stakeholders Engagement and Awareness

To understand the degree of stakeholders' awareness and engagement in practice, the following analysis was conducted. Findings related to the types of stakeholders involved in the different projects are presented in Figure 6. In total 12 types of involved stakeholders were identified in the projects, with public authority bodies and private enterprises having the lion's share of participation while individual citizens are the least represented, confirming the lack of horizontal acceptance of NBS. NBS as a concept is multidimensional and its implementation requires collaboration amongst different policy areas, sectors and stakeholders (Van Ham and Klimmek 2017). More precisely, Figure 6 shows that the most represented type of stakeholder identified in the analysed projects was Local public authority (88.9%). Private enterprises hold the second place (81.5%), followed by Research and educational institutions (66.7%) and Planners (63%) while, on the place are National public authorities (18.5%).

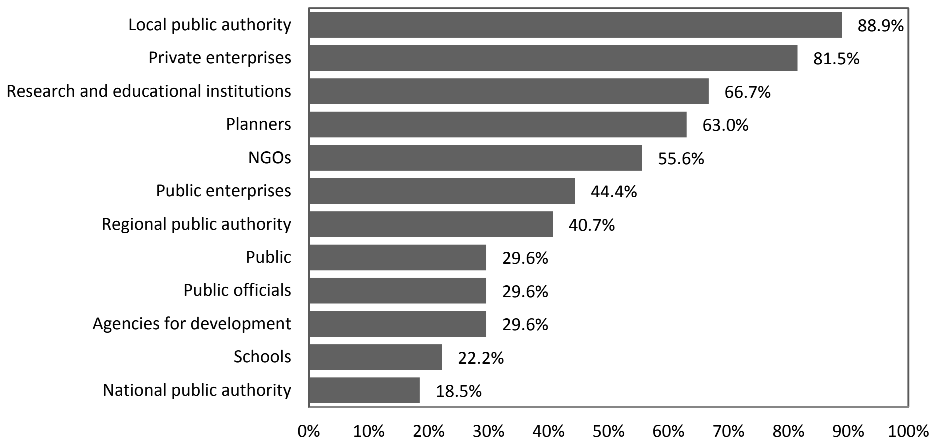

Figure 9: Types of stakeholders involved in the projects

Regarding the barriers for the implementation of project activities related to stakeholder's awareness and engagement in the analysed projects (respondents could choose multiple answers), unsupportive legal frameworks (45.8%) and insufficient financial resources (45.8%) are identified as the main issues (Figure 7). These findings are further supported by literature, e.g. Brink et al. (2016) indicates that the lack of resources, know-how, tools, unsupportive legal frameworks are, among others, serious impediments to NBS implementation. Lack of time holds third place with 33.3%, followed by lack of basic knowledge about NBS (29.2%) and Lack of engagement plan (25%). Combination of the previously mentioned five barriers for stakeholder's awareness and engagement is present in almost every project.

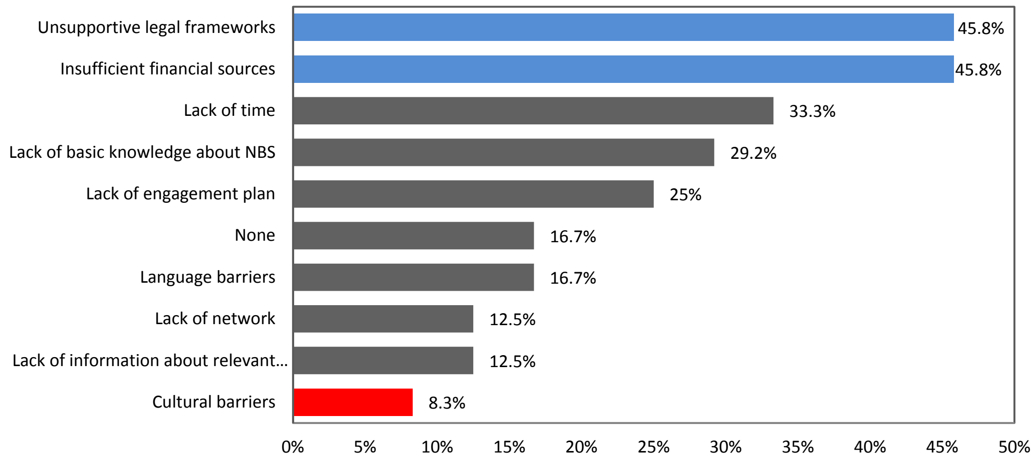

Figure 10: Barriers to the implementation of project activities related to stakeholder's awareness and engagement

Figure 8 presents the most common participation tools and techniques that are used in the projects for stakeholder's awareness raising and engagement on NBS. Among others, respondents identified Participatory workshops (63,6%), Internet (45,5%), Public meetings (45,5%), Printed information (e.g. brochures, leaflets, newsletters) (40,9%) and Regional focus groups events (27,3%) are the most common participation tools and techniques used for stakeholder's awareness and engagement on NBS. Besides these five categories, there were also external events (e.g. fairs, promotions, exhibitions), telephone contact, newspaper and semi-structured interviews, represented with less than 25% in provided answers. Results from Figure 10 indicate a shift from "traditional techniques and tools", such as telephone and printed media, to the increased use of social media and the internet. The fact that social media and internet are more popular probably also depends on the type of stakeholders that are commonly engaged in participatory events (youth and urbanized population) while, older population favours printed media. It is important to consider that a "participation divide" (Hargittai and Walejko 2008) between elders and youth, urban and rural, and middle-high and low income affects such a result (Hargittai 2002)((Paul and Stegbauer 2005; Sylvester and McGlynn 2010)). Further research might be useful for future NBS implementation considering different groups of stakeholders.

According to the International Association for Public Participation, there are five levels of stakeholder's engagement, i.e. inform, consult, involve, collaborate and empower (International Association for Public Participation (IAP2) 2007). According to this categorization, the level of stakeholders' engagement in the analysed projects was identified (Figure 9). It should be noted though that the results only represent the respondents' perception regarding the level of stakeholders' engagement in their project.

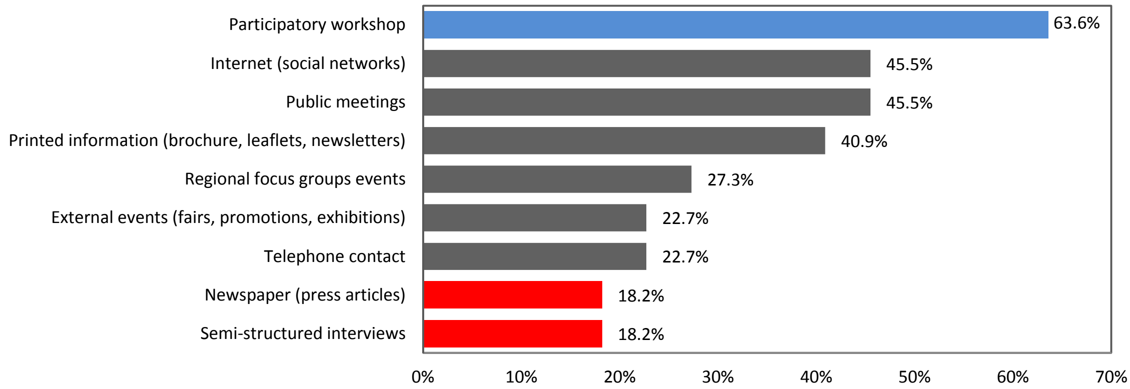

Figure 11: Public participation tools and techniques used in the project for stakeholder's awareness raising and engagement on NBS

In the majority of the projects (31%), stakeholders were informed in order to understand the problem, alternatives, and opportunities related to NBS. In 13.8% of the projects, stakeholders had a consulting role in order to provide feedback on the analysis, the alternatives and/or the decisions related to NBS. 20.7% of the respondents involved stakeholders in their projects to work directly with them throughout the process in order to ensure that stakeholders' concerns and aspirations about NBS are consistently understood and considered. In 27.6% of the projects, collaborative methods (e.g. collaboration for the development of alternatives, identification of preferred solutions) – which help mobilize stakeholders and build capacity to deliver projects (Healey 1998) – are deployed in stakeholders' engagement. Regarding the highest level of stakeholders' engagement, only 6.9% of the respondents empowered stakeholders in their project to make a final decision.

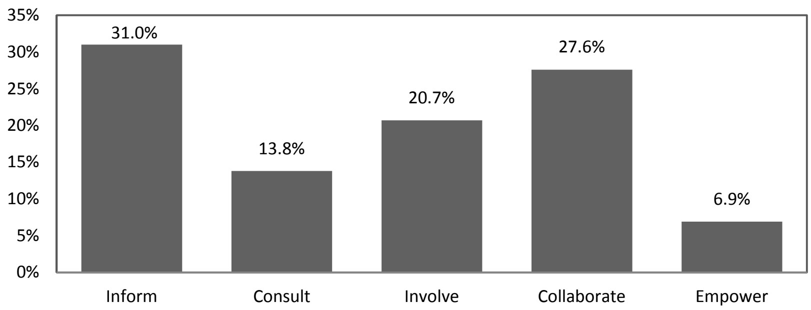

Figure 12: Level of stakeholder engagement in the projects.

Results of cross-tabulation analysis between the different types of the projects and level of stakeholders' engagement are presented in Figure 10. The results of this analysis reveal that Research and Innovation projects engage the highest number of stakeholders and among them, in 20.7% of the R&I projects stakeholders were informed, in 10.3% they were consulted, in 10.3% they were involved, in 13.8% they collaborated and in 6.9% stakeholders were empowered.

An additional cross-tabulation analysis between the level of project's implementation and the level of stakeholders' engagement (Figure 11) reveals that projects implemented at macro level (city, regional) engaged the highest number of stakeholders out of which, 20.69% were informed, 6.9% were consulted, 10.34% of the stakeholders were involved, 10.34% were collaborated and 3.45% were empowered.

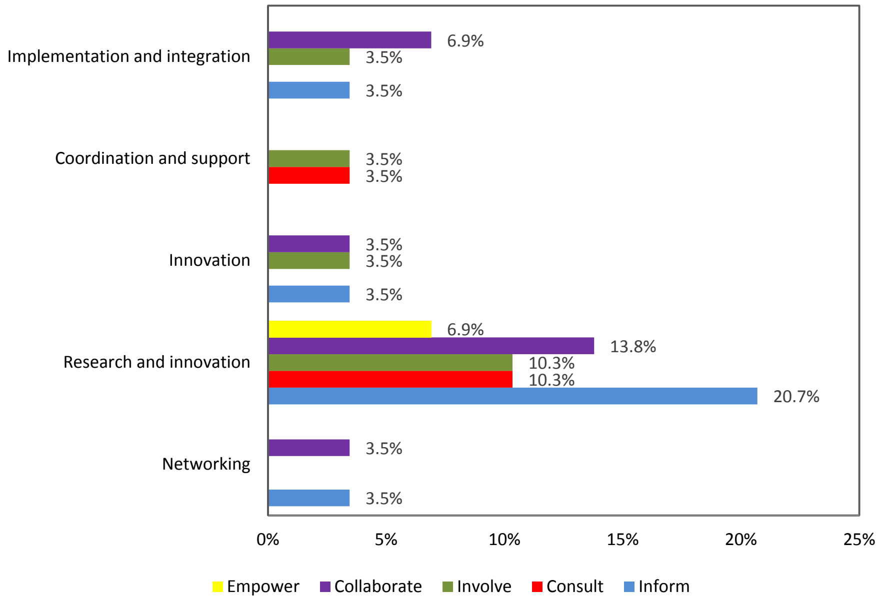

Figure 13: Cross tabulation between the type of the project and level of engagement

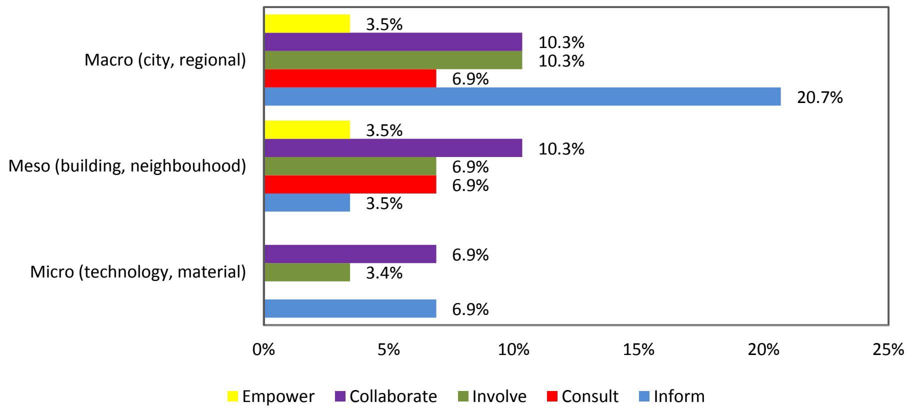

Figure 14: Cross tabulation between application scale of the project and level of engagement.

6.5.3. Tools and Methods

To understand which assessment methodologies are mostly employed in practice, the following analysis was conducted. The assessment methodologies that are applied in the targeted projects are presented in Figure 12, indicating that a wide variety of assessment methodologies is used. In general, it is worth noticing that the assessment of NBS is mostly focused on the environmental and economic aspects, while the social aspect of the NBS implementation is underestimated (i.e. 12.5% of the projects conducted S-LCA) in the projects. More precisely, most projects apply one of the following assessment methodologies: i) LCA (39.3%), a well-established method for sustainability assessment; ii) Cost Benefit Analysis (30.4%), in order to prove the cost effectiveness of the implemented solutions; and iii) Mapping and Assessment of the Ecosystem Services (MAES) (33.9%), as the enhancement of the ecosystem services is the cornerstone of NBS. MFA is also considerably applied in the projects (25%), which can be explained by the fact that it is another well-established method to measure the circularity of systems (EC 2015b; Linder, et al. 2017). Consequently, it can be argued that in practice (i.e. implementation of a project) well-established methods are more favorable compared to other newly developed methods (e.g. HHA, or SS) or to methods that are not directly linked to NBS or circularity assessment (i.e. Urban Metabolism).

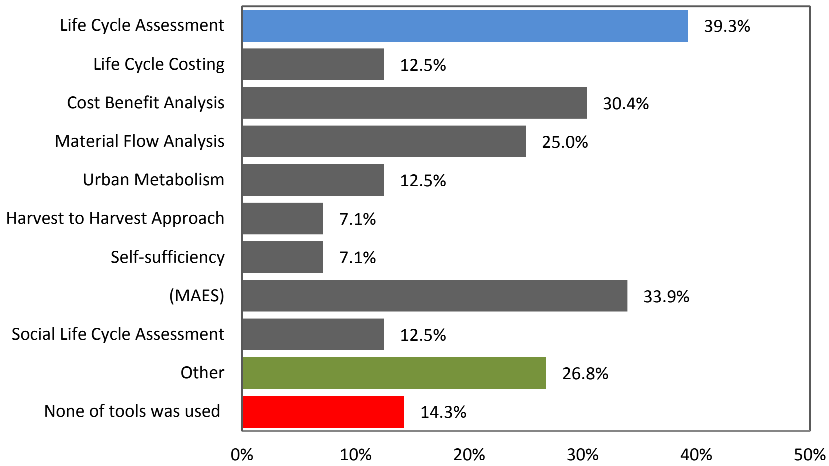

Figure 15: Methods used for the assessment of the applied solutions

Regarding the application scale of the projects (Figure 3(c)), several projects were carried out on-ground. As those projects might be very useful for the transferability of the concepts of NBS for Circular Cities, a further analysis of the results of on-ground projects regarding their application scale was carried out. Figure 13 shows that 52.6% of these on-ground projects have been applied on a macro scale, and 39.5% of them have been applied on a meso-scale.

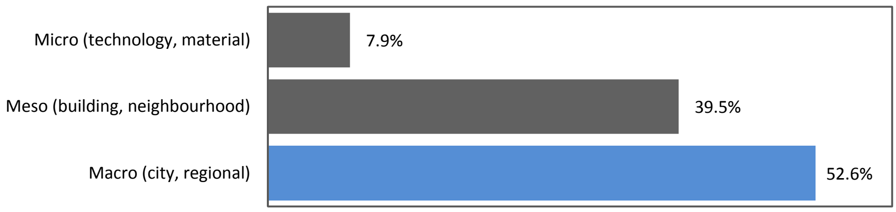

Figure 16: Distribution of on-ground projects regarding their application scale

The methodologies that have been used in on-ground projects to assess the effectiveness of the applied technologies with regard to their application scale are summarized in Figure 14 – (left) assessment methodologies applied on a meso-scale, and (right) assessment methodologies that have been applied on a macro-scale.

Meso-scale projects (Figure 14-left) mostly use Life Cycle Assessment (LCA) (46.7%) to assess the sustainability of their proposed technologies, while 40% of these projects additionally use material flow analysis (MFA). It is evident that the economic aspect is underestimated among these projects, since 20% use Cost-benefit analysis (CBA) and only 6.7% use Life Cycle Costing (LCC). In contrast, this trend changes significantly when on-ground projects applied on a macro-scale. In this case (Figure 14-right), the most widely applied methodology is the Mapping and Assessment of Ecosystem Services (MAES) and only 35% of the projects use LCA. Ecosystem Services are implemented in larger scales (e.g. catchment-scale, watershed-scale etc.), while in a smaller scale (e.g. neighborhood scale) only the relative changes in ecosystem services can be assessed. LCA on the other hand, is mostly used to assess the sustainability of specific systems (meso-scale), e.g. Wastewater Treatment

Plants. Although LCA can be applied on larger scales as well, there are only a few studies that have performed this type of analysis. For example the study of Lane (Lane, et al. 2015) includes the assessment of the environmental impact of a broad range of technologies at the "whole-of-system" level - urban water system. Therefore, the change in the preference of the assessment methodologies would be better explained if the assessment scale is also known. In case that the assessment scale coincides with the application scale of the technologies, then the reason behind this change in preferences is clear. Moreover, on-ground projects at macro scale are more focused on the economic aspect of their technologies, as 40% of these projects use CBA.

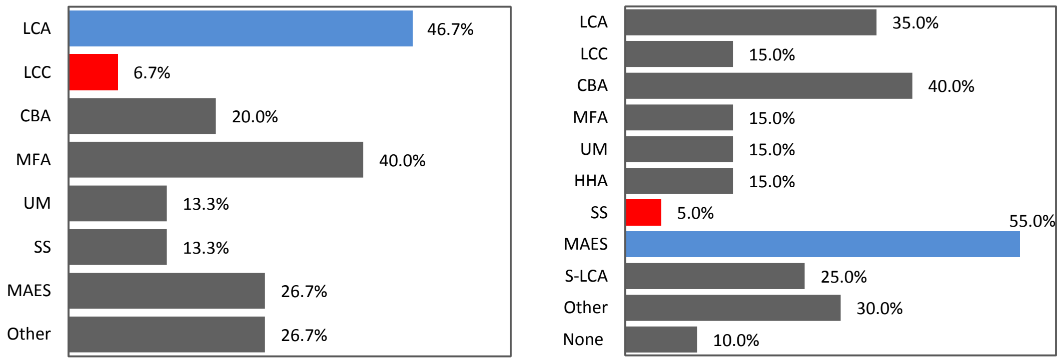

Figure 17: Assessment methods for on-ground projects on meso- (left) and macro-scale (right)

Some useful ICT tools were used and reported in these projects too. They can be grouped as (i) data or databases (including GIS for 3D visualization, weather gridded, energy carbon footprint, data mining sensors, cloud-based geo-referenced system for storing & communicating the acquired water quality information, or websites containing data for mapping of pilot areas), (ii) models (for temporary housing, climate adaptation, water management strategies or for gamming in some apps), (iii) monitoring and control systems (for online greenhouse gases emission in wastewater treatment plants based on wireless sensor networks, for ecosystem services adapted to urban areas, for real-time flood mitigation, for waterloops or for automation and process control in general), (iv) decision suport sytems to select among alternatives or to identify potential pollutant sources & predict the effectiveness of mitigation measures. Comercial software (e.g. simulistics, UnicaLids or matlab, etc.) and platforms with open-source information (e.g. OPPLA, think nature, Tygron, ICT governance, or for e-learning courses like ed XMOOCs) have been also reported for the implementation of NBS.

6.6. Conclusions

Adoption and implementation of NBS in Circular Cities is circular itself and require four main steps, i.e. planning, design, assessment, and communication. Policies and regulations, stakeholders' engagement and awareness, and tools and methods assessing the socio-economic and environmental impacts of the solutions are integral parts of this circular process.

The state-of-the-art analysis performed in the present paper, revealed that limited research has been conducted on "policies, regulations and governance" for deploying NBS to move towards Circular Cities; a deeper analysis is still required. Circularity initiatives and NBS imply risks and unknowns, compared to classical solutions, and are not compatible with current rules and regulations. The survey results confirmed these findings revealing that many of the current policies and regulations are almost equally perceived as both limiting and enabling the development of NBS. Experimentation zones where these prevention principles and regulations are not (fully) applicable for specific projects could be a solution. The EU is moving in that direction with the "innovation deals" initiative, in particular one launched on treated wastewater reuse.

The literature revealed that public awareness and social acceptance are key issues related to the success of NBS for Circular Cities, as they can reduce barriers to NBS adoption and diffusion on a wider scale of application. Respectively, the projects' survey demonstrated that the level of stakeholders' engagement is very important in order to achieve accepted outcomes as well as for successful project delivery. However, unsupportive legal frameworks and insufficient financial sources were identified as the main barriers related to stakeholder's awareness and engagement. The projects' survey demonstrated that participatory workshops, social media and public meetings are the most common public participation tools and techniques used in the projects for raising stakeholders' awareness and engagement. Therefore, this study implies that such tools should be further investigated with regards to each one of the four steps for NBS application so that their utilization is more productive.

The analysis of existing tools advocates more quantitative upscaling of NBS technologies, although research and innovation in this field seems to be still at an infancy stage. An extensive diversity of tools and methods assessing the impacts of NBS was identified in the literature, as well as in the selected projects, which complicates the comparability and measurability of such projects, as well as their transferability on a wider scale. However, based on the results from the survey it was found that the assessment methods that are mostly used are the ones that are well-established, such as LCA, CBA, MFA, while recently developed methodologies (e.g. HHA) are not in favour even though they may be very prominent for the assessment of NBS for creating Circular Cities. Interestingly, it was found that the decision on the employed methodologies is related to the application scale of the project. A further and more focused analysis on the nature of tools applied for every step of the application of NBS i.e. planning (routinely considering NBS, integrate triple benefits targets: economy, community and environment, build new partnerships to bring new resources and skills), design (using advanced tools and guidelines integrating NBS), assessment (learning new lessons for closing the knowledge gap, and communication (engaging policy makers, building capacities), would lead to a more straightforward methodology. More specifically, the development of a widely accepted methodology or framework for assessing NBS for Circular Cities would provide the guidelines regarding the hybridization of the different methods and it would systematize the evaluation of the effectiveness of NBS for creating Circular Cities.

Improving knowledge on the impact of NBS is moreover, necessary for decision-makers to prepare a transition process to circular systems. The EU is leading a wide range of developments in particular with enabling environments (e.g. policies, innovation funds), while at the global level, IUCN (IUCN 2012; Cohen-Schacham et al. 2016) and the World Bank (WB 2019) are advocating for NBS to be more integrated into new initiatives, in particular infrastructure projects.

Continuous monitoring that would be enabled through the use of ICT tools and evaluation of the implementation of NBS for circular cities will support the development of a solid knowledge base for more suitable policies and regulations.

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6.8. Disclaimer

The content of this article is the authors' responsibility and neither COST nor any person acting on its behalf is responsible for the use, which might be made of the information contained in it.

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6.10. Appendix 1. List of reviewed projects collected from the survey

No.	Project Title	Project Acronym
1	Implementing nature based solutions for creating a resourceful circular city	Circular City Re.Solution (CA17133)
2	Recovery and utilisation of nutrients 4 low impact fertilizer	Run4Life
3	productive Green Infrastructure for post-industrial urban regeneration	proGIreg
4	The effect of agricultural and rural development policy on local small-scale agrifood production	SmallScaleFarm
5	Fate and Toxic Effects of Silver Nanoparticles and Its Transformation Products in Soil Applied with Biosolids	TESNinSAB
6	farmAR app satellite based farming guidance	farmAR
7	Clean Technologies for Sustainable Environment - Water, Waste, Energy for Circular Economy	Clean & Circle
8	The Productive Decentralised Wastewater System - New Value Chain for Urine Based Fertilisers	Urine Drying
9	Inventorization of Trees as part of the Skopje Green Cadaster	Skopje Green Cadaster
10	Water Absorbing Geocomposites – Innovative Technologies Supporting Plants Vegetation	HYDROBox
11	Hydroponics and sustainable crops on rooftops of buildings in the city	METEORA
12	Responsible water management in built-up areas in relation to the surrounding landscape	SWAMP
13	Urban pop-up housing environments and their potential as local innovation systems	Pop-up housing
14	Sfax Future Circular City	SFCC
15	COproductioN with NaturE for City Transitioning, INnovation and Governance	CONNECTING Nature
16	Demonstration of water loops with innovative regenerative business models for the Mediterranean region	HYDROUSA
17	Closing material flows by wastewater treatment with green technologies	GreenT
18	Tartu	Tartu
19	Vertical greening for liveable cities – co-create innovation for the breakthrough of an old concept	Vertical Green 2.0
20	Feeding Sustainable Cities	FSC
21	Towards water autarky: Recycling of (gray)water	Local Water Loop
22	Smart integrated multitrophic city food production systems –a water and energy saving approach for global urbanization	CITYFOOD
23	Biochar for Urban Trees	-
24	New Strategy for Re-Naturing Cities through Nature-Based Solutions	Urban GreenUP
25	VertikaleKlimaKlärAnlagezurSteigerung der Ressourceneffizienz und Lebensqualität in urbanenRäumen / Vertical Climate Treatment Plant for increasing resource efficiency and livability in urban area	VertiKKA

26	Wider business Opportunities for raw materials from waste Water.	WOW
27	Urban Allotment Gardens in European Cities	COST Action TU1201
28	Recovering valuable resources from industrial effluents	SELENEX
29	Natural Water Retention Measures	NWRM
30	Coast to Coast Climate Challenge	C2C-CC
31	Edible Cities Network Integrating Edible City Solutions for social resilient and sustainably productive cities	EdiCitNet
32	Nature Based Solutions for re-naturing cities: knowledge diffusion and decision support platform through new collaborative models	Nature4Cities
33	Urban Platform for Circular Economy	UPCE
34	Potential and Validation of Sustainable Natural & Advance Technologies for Water & Wastewater Treatment, Monitoring and Safe Reuse in India	PAVITR
35	Houseful: Innovative circular solutions and services for new business oppor-tunities in the EU housing sector	Houseful
36	Circular economy to facilitate urban water reuse in a touristic city: centralized or decentralized?	CLEaN-TOUR
37	Ecosystem Service Toolbox developed from multi-scale Integrated Modelling of Urban Metabolism	ESTIMUM
38	GestioneIntegrataAcquaRinverdimentoEnergia	G.I.A.R.E.
39	HydroResilience	HydroResilience
40	Kräfte in pflanzenbewachsenenSeilfassaden und – strukturen – ExperimentelleUntersuchung und EntwicklungeinesLastmodells und Bemessungskonzepts	Kräfte in pflanzenbewachsenen Seilfassaden
41	Carbon neutral next generation wastewater treatment plants	CarbonNextGen
42	Vegetated systems as urban solutions for water management	SUWAM-Solutions for Urban WAter Management
43	Unalab	unalab
44	The Concept of Livability in the Context of Small Towns	LIVA
45	Nature-based solutions for increasing cities resilience and sustainability	NaturB
46	Going Outdoors: Gathering Research Evidence on Environment and Nature	GO GREEN
47	IMAGINE	IMAGINE