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COMMUNICATIONS

Nature-Based Solutions and Circularity in Cities

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Abstract
Cities worldwide are facing a number of serious challenges including population growth, resource depletion, climate change, and degradation of ecosystems. To cope with these challenges, the transformation of our cities into sustainable systems using a holistic approach is required. The pathway to this urban transition is adopting the concept of circular economy for resource management. In this way, resources are kept and reused within the city. Nature-based solutions can be implemented for these tasks, and besides the circularity, they can provide additional benefits for the urbanites and the urban environment in general. This paper describes which urban challenges related to circularity can be addressed through nature-based solutions. This systematic review was developed within the COST Action CA17133 Circular City that investigates how nature-based solutions can be used to progress the circular economy in the urban built environment.

Keywords Circular economy · Circular cities · Nature-based solutions · Urban circularity challenges · Water-food-materials-energy management · Circularity assessment

Introduction

Linear management of resources (water, food, materials, energy) in cities contributes to the global environmental problems, such as resource depletion, ecosystem degradation, biodiversity crisis, and loss of the natural capital. This leads to a growing demand for resources on one hand and waste production on the other—all in the name of eternal economic growth. In response, the adoption of the circular economy (CE) model is proposed, which provides economic growth without increasing the consumption of new resources and reducing the impact on the environment [1–3]. At the core of CE are the three principles identified by the Ellen MacArthur Foundation [4], namely, 'Regenerate natural capital', 'Keep resources in use', and 'Design out waste externalities'. 'Regenerate natural capital' ensures functional

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Extended author information available on the last page of the article environmental flows and stocks, by reducing the use of resources, preserving and enhancing ecosystems, and ensuring minimum disruptions from human interactions and use. The goal of 'Keep resources in use' is to close material loops and minimize energy loss within the system, which is achieved by optimizing resource yields, optimizing energy and resource extraction, and maximizing their recycling and reuse. 'Design out waste externalities' focuses on the reduction and the remaining waste of the system, including the economic efficiency; namely, the costs of reducing waste by one unit is equal to the economic and environmental benefits of having one less unit of waste [4].

Current management of resources in cities is based on infrastructures which cannot fulfil these principles because they work in a way that (1) resources are imported and delivered to consumers, after use and treatment, they are discharged as residual (linear management), and (2) existing infrastructure only has the single-functionality it is designed for (e.g., wastewater treatment or urban drainage). In order to comply with the three principles of the CE, substantial changes in the infrastructure design and management are needed by using a multisectoral and multidisciplinary approach.

The concept of nature-based solutions (NBS) has been on the spotlight recently, because of its high potential to address several urban challenges such as climate mitigation, air quality, water management, participatory planning, and governance [5]. One of the most appreciated characteristics of NBS are their co-benefits and multifunctionality. Despite being designed for specific purpose (e.g. urban drainage), NBS can deliver several ecosystem services at the same time (e.g., treatment, evaporative cooling, and biodiversity). A single element can serve as insulation for a building and a wastewater treatment plant at the same time [6–10].

Multifunctionality makes NBS an important concept for cities to achieve resource management according to the CE principles. Even though NBS concept has been used for decades, for instance, under the frame of similar concepts such as ecological engineering, green infrastructure, urban green (and blue) spaces, and ecosystem-based adaptation [10], there are several barriers for its systemic implementation (legislation gaps, lacking capacities and skills, unawareness, too sectoral approach to resource management, etc.). However, one of the biggest is the existing infrastructure itself. Introducing NBS and different resource management can cause problems in the functioning of existing infrastructure, as resources flow to which the existing infrastructure was designed for change in their quantity and quality. Therefore, NBS should be introduced with expert knowledge, leading not only to modifications but to new (hybrid) systems to holistically contribute to the three CE principles.

In this communication, we describe which urban challenges related to circular management of resources can be addressed with NBS. The concept, relating urban challenges with NBS, was developed within the COST Action CA17133 Circular City investigating 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' [11]. Additionally, we show examples of NBS enhancing circularity in urban areas and discuss how circularity in cities can be assessed.

Urban Circularity Challenges

In the context of circular cities, CE is viewed as a mechanism that helps cities to shift from linear to circular resource management. Two major urban circularity challenges are addressed by circular cities, namely, (1) preserving natural resources by reducing their import and (2) minimizing waste production by using resources in cycles. Both challenges are generic and need specification for different resources' streams (water, food, materials, and energy) as illustrated in Fig. 1. Nature-based solutions are placed in the scheme as means for addressing the challenges.

The following urban circularity challenges (UCC) for shifting to circular management of resources can be addressed with NBS:

- Restoring and maintaining the water cycle (by rainwater management)
- Water and waste treatment, recovery and reuse
- Nutrient recovery and reuse
- Material recovery and reuse
- Food and biomass production
- Energy efficiency and recovery
- Building system recovery

(1) Restoring and maintaining the water cycle (by rainwater management)

Water in nature represents one big cycle maintained by natural processes (condensation, precipitation, infiltration, evapotranspiration, and runoff). Cities interrupt this cycle by creating

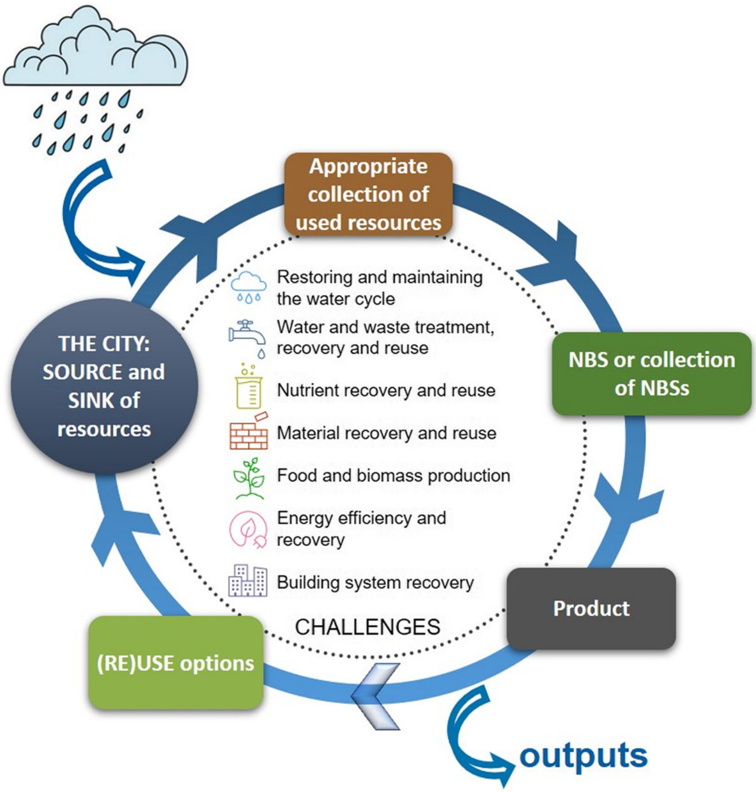

Fig. 1 Urban circularity challenges for shifting to circular management of resources of cities that can be addressed with nature-based solutions

impervious areas, which prevent infiltration and increase surface runoff. As a result, cities provide rainwater management services in a form of sewer networks that drain the city, to protect citizens from floods. However, this type of urban drainage has proven insufficient at extreme (sometimes already at slightly stronger than average) rain events, which result in surface runoff that cannot be entirely drained by a sewer network. As a consequence, we witness frequent pluvial floods in cities, erosion, pollution in downstream watercourses due to combined sewer overflows, and malfunctioning of hydraulically overloaded wastewater treatment plants. From the CE aspect, the water management services need to include and adopt rainwater management services that provide more retention and infiltration in the city by mimicking the natural processes and thus restore and maintain the natural water cycle processes.

(2) Water and waste treatment, recovery, and reuse

Another way of interrupting the water cycle is that cities import water to supply their citizens and generate wastewater. Wastewater (i.e., water enriched with organic matter and nutrients originating from consumed food) is transported to treatment plants and then discharged to the environment leaving behind nutrient and organic rich by-products (e.g., sludge). The challenge is how to manage wastewater to safely reuse water and by-products instead of importing new water and nutrients. From the CE aspect, the water services should shift from treatment for disposal to management for reuse. This concept not only requires a different conceptual approach as reuse requires additional infrastructures but also indicates a shift to 'selling less water' and 'providing more services'.

(3) Nutrient recovery and reuse

Nutrients enter cities mainly through imported food. After being consumed and metabolized, they end up in wastewater. The challenge is to avoid flushing the nutrients with wastewater and keep them in the city. One of the most efficient ways of nutrient recovery is the separation of different waste streams (urine, faeces, and greywater) which requires substantial changes in the water management and its infrastructure.

(4) Material recovery and reuse

Modern building materials rely heavily on nonrenewable resources while materials from demolition sites are often disposed at the landfills. Nature-based solutions can be used to address this issue by dedicated reuse of demolition material as filter media, using recycled building materials such as wood, metal, or plastic as well as by producing biocomposite additives for the vast amount of produced concrete and isolation materials.

(5) Food and biomass production

The benefits of urban food production are numerous. Urban farming can be used as a part of the systemic solution for sustainable management of resources, contributing to a circular urban metabolism and complying with CE principles. And yet, urban food production as systemic solution is still a challenge for cities. By applying the CE concept, urban food production is practised from local resources, meaning reusing water and nutrients from waste streams, which encounters many barriers from legal and technical, health safety to social acceptance.

(6) Energy efficiency and recovery

The main challenge from CE viewpoint related to energy is reduction of demand for imported (fossil fuel based) energy. Energy efficient buildings, mitigation of urban heat island effect and consequently, reducing the demand for cooling in buildings, and heat and energy recovery from different waste streams are foreseen goals that can be achieved with NBS in a circular concept.

(7) Building system recovery

Although CE itself does not distinguish between the scales of circularity, building reuse has often been agreed upon as a preferred option over material and component recycling, thanks to its higher up-scaling potential. This is particularly true for 'Heritage' buildings and neighbourhoods. In urban regeneration projects, NBS can effectively be used to address this issue. Circular buildings impact positively on materials, energy, waste, biodiversity, health and wellbeing, human culture, and society at once. Additionally, they may produce multiple forms of value [12].

Nature-Based Solutions for Urban Circularity Challenges

Among many definitions of NBS, there is one predominant agreement, i.e., bringing nature in cities. 'Nature' is often understood as 'the green factor′ indicating presence of vegetation [13]. Nevertheless, such statement might eliminate a full range of solutions that employ nature via natural processes, such as microbiological processes or for example (bio)filtration through natural porous material. A good example of this is a wastewater treatment pond (lagoon), where the treatment is performed by microbes. The role of natural, nonintensive processes (microbial biodegradation) is evident, yet the requirement for 'greening' is not fulfilled.

To address this conceptual gap, the COST Action Circular City put forward a novel definition which includes solutions without the 'green factor' to support and facilitate the implementation of circularity with NBS. Nature-based solutions are defined as concepts that bring nature into cities and those that are derived from nature [11]. Nature-based solutions 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 they may be needed for supporting and enhancing the performance of NBS.

To clarify the meaning of the NBS concept is as important as defining a common set of NBS in order to facilitate its implementation and monitoring. In this sense, Castellar et al. [13] propose a common list of 32 NBS, by revising more than 200 NBS defined in four European projects (UNALAB [14]; NATURE4CITIES [15]; THINKNATURE [16]; URBANGREENUP [17]). Moreover, the authors disclose a conceptual advancement in terms of understanding the role of NBS in urban settlements by proposing two novel typologies: NBS units (NBS_u) and NBS interventions (NBS_i).

According to Castellar et al. [13], NBS_u stands for single green technologies (NBS_technological units (NBS_tu)) or urban green space (NBS_spatial units (NBS_su)) replicating processes occurring in nature to enhance the performance of natural capital in cities. Their implementation can be either as a single unit or in combination with other NBS, conventional technologies or existing urban infrastructures [13], and thus, such classification is in line with the principles of CE. NBS interventions refer to measures and bioengineering techniques applied in specific ecosystems or other NBS_u to support natural processes such as river flow dynamics (NBS river interventions (NBS_ri)), soil quality (NBS soil interventions (NBS_si)), and biodiversity (NBS biodiversity interventions (NBS_bi)) [13]. This conceptual framework was built in the frame of the COST Action Circular City, in order to support the selection and characterisation of NBS_u and NBS_i, with potential to tackle urban circularity challenges (UCC), i.e., to create a list of NBS under the 'NBS Circular Framework'.

In Table 1, we describe which circularity challenges can be addressed by 12 selected NSB_u and NBS_i. For example, extensive and intensive green roofs both address the water cycle and energy efficiency and recovery challenges; however, when using intensive green roofs, also other UCC can be addressed. Large urban parks contribute to water management and heat regulation; however, they can also be fertigated with treated water and can include fruit trees as well as structures (hills, banks, etc.) made from waste construction material. The estimation on how NBS address UCC was developed in the COST Action CA 17133 within dedicated workshops.

Contribution of Nature-Based Solutions Towards Circularity

Introducing NBS into cities for managing resources according to the three CE principles leads to reshaping the existing linear management into circular one. Nature-based solutions play an important role at 'keeping resources in use', mainly through recovering and reusing water and nutrients from, e.g., wastewater and producing valuable by-products, namely, providing reclaimed water, biomass, and organic fertilizers and giving new applications to waste materials generated by other local production chains like reusing recycled materials for building NBS structures or reusing granulated waste as filter media [18].

In particular, their multifunctionality opens a whole range of implementation possibilities. Nature-based solutions for wastewater treatment have great potential for additional benefits such as provision of healthy ecosystems, energy savings, biodiversity, and air quality [19–21]. For example, green wall systems, despite providing thermal regulation and reducing energy expenditure, can also treat urban wastewaters such as greywater and, thus, reduce the demand for potable water for non-potable use [18, 22–24]. In addition, NBS for wastewater treatment also have potential to recycle and recovery of resources contained in domestic wastewater as for example, by transforming organic material into bioenergy and recovering nutrients such as nitrogen, phosphorus, and potassium [20]. Nutrient recovery and reuse play a major role on minimizing the production of manufactured nutrients and thus reducing related CO_2 emissions and energy demand, as well as contributing to reduce the accumulation of reactive compounds into environment.

In short, the key message is that NSB outputs can be transformed into valuable products and re-enter the value chain (reclaimed water, biomass and organic fertilizers, etc.); moreover, the outputs from other local production chains can be absorbed by NBS. Few studies have shown the potential of using recycled material for structure of green walls such as polyethylene modules [25], recycled PET bottles [26], or cork boards [27]. Nowadays, there is also a great variety of waste materials being tested and validated in terms of their performance to be used as filter media in NBS: cork [28], coconut shell [23], recycled glass beads [29], mix of coir fibber and perlite [30], and crushed autoclaved aerated concrete [31]. One can conclude that creating new applications to waste materials is the basis for the establishment of an integrative urban chain, where the demand for manufactured products and disposal of waste is reduced.

Table 1 Urban circularity challenges addressed by selected NBS units and NBS interventions (● = addressing the challenge; ● = contribution to challenge mitigation; ○ = potential contribution, depending on the design)

NBS name	Category	Circularity challenge						
		Restoring and maintaining the water cycle	Water and waste treatment, recovery, and reuse	Nutrient recovery and reuse	Material recovery and reuse	Food and biomass production	Energy efficiency and recovery	Building system recovery
Infiltration basin	NBS_tu	●	●				●	
Bioretention cell (rain garden)	NBS_tu	●	●	●			●	○
Soil/ground-based green facade	NBS_tu	●					●	●
Wall-based green facade	NBS_tu	●	○	○	○	●	●	●
Extensive green roof	NBS_tu	●					●	●
Intensive green roof	NBS_tu	●	○	○	○	●	●	●
Large urban park	NBS_su	●	○	○	○	○	●	
Productive garden	NBS_su	●	○	○		●		○
Composting	NBS_is		●	●	●		●	
Erosion control	NBS_is	●	●	●				
Floodplain	NBS_ir	●	○			●	●	
Diverting and deflecting elements	NBS_ir	●						

The ‘Universidad Loyola Andalucía’ Case

The ‘Universidad Loyola Andalucía’ (Figure 2A) conceived its built infrastructure in the campus of Seville (southern Spain), considering the solar influence as a key weather-related condition. Thus, textile technologies, i.e., sails and overhanging elements, control the sunlight preventing excessive heat gains through the facades. The sustainability aspect of the campus, as an answer to the energy and heat circularity challenge, is designed to ensure energy efficiency by consuming around 40% less energy than similar buildings. Roofs, facades, and windows are designed to minimize the net energy consumption–reflective colour of the roof materials and installation of photovoltaic panels with maximum production of 150 kWp. More than 20% of the building materials are reused, supporting the material recovery challenge, and more than 30% were produced within 800 km from the university complex minimising the environmental effects of the material transport. Regarding the efficient use of water, both restoring the water cycle by rainwater management and water and waste treatment and reuse challenges including the use of treated greywater for toilet flushing have been planned [32, 33].

The ‘Boutiquehotel Stadthalle’ Case

The ‘Boutiquehotel Stadthalle’ (Fig. 2b and c) located near the centre of Vienna (Austria) represents an example of zero-energy balance and urban environmental protection (see neZEH [34] for more information). Water and energy consumption at the hotel is reduced by using a groundwater heat pump, three wind turbines, photovoltaic technology (integrated photovoltaic system of 13 kW), and 130 m^2 solar panels, which produce clean electricity and hot water: eco-shower heads, LED light bulbs, and standby mode devices as an example of energy and heat circularity challenge. Water from the well is used to irrigate the interior courtyard garden and to flush the toilets. Moreover, the hotel saves 21 kg CO_2/room and separates and recycles 100% of the organic waste produced by composting. The hotel garden stands out for its big trees, lavender roof and walls covered by ivy, urban trees and gardens, green roofs, and walls NBS units, according to Castellar *et al.* [13] supporting urban biodiversity (birds, bees, and butterflies) and offering a variety of ecosystem services. Fresh herbs are grown in the interior courtyard; lavender is harvested from the green roof, dried, and used to scent the hotel rooms and as an ingredient in the hotel kitchen; honey produced is consumed at the hotel breakfast service, as an example of food and biomass production UCC proposed [35, 36].

Assessing Circularity in Cities

To assess circularity in cities by considering the implementation of NBS, one needs to understand what should be measured from a circularity perspective and how NBS can enhance circularity. Therefore, a selection of specific circularity targets is required, identified in this work as the three CE principles developed by Ellen MacArthur Foundation [4]. Nature-based solutions, if properly designed and locally adapted, mainly build on the regeneration of natural capital and environment, facilitate the transition from linear to circular management of natural resources, and reduce externalities by reducing energy and heat consumption and by using recovered materials as building materials for their construction. However, the current approach to CE focuses mainly on the consumer products industry (textiles, plastics, electronics, batteries, vehicles, packaging, etc.), lacking a direct link to NBS. The new EU Circular Economy Action Plan [37] introduces

Fig. 2 Implemented cases using nature-based solutions aim to enhance urban circularity challenges: **a** East façade of the 'Universidad Loyola Andalucía' main building at its campus from Seville, Spain (original photograph provided by 'Universidad Loyola Andalucía'-'Víctor Sájara Photography'); and Boutiquehotel Stadthalle in Vienna, Austria: **b** interior courtyard garden and **c** exterior façade with detail of the photovoltaic system and green wall (both photographs were taken by Rocío Pineda-Martos in February 2019)

Construction and Buildings as well as *Food, Water, and Nutrients* as two additional key product value chains that require circularity actions. Although NBS seem to be relevant for these two key product value chains, the Action Plan lacks any reference to NBS. NBS are reported in the European

Green Deal [38] as enablers to two out of the eight objectives – i.e. *Increasing EU's climate ambition* and *Preserving and restoring ecosystems and biodiversity* – but their relevance in achieving the *Clean and circular economy* objective is again disregarded. Evidently, NBS struggle to find their position within the concept of CE.

Nature-based solutions are thus rarely assessed from a circularity perspective. Most studies focus on the main societal challenge addressed by NBS and evaluate their performance based on technical characteristics only, underestimating the enhancement of the natural environment and many of their co-benefits [39]. Another issue is that NBS_u and NBS_i are assessed as individual components, neglecting upstream and downstream processes and flows, and the interconnections and feedbacks between these processes and, consequently, the impacts to the system as a whole. A fragmented approach of understanding isolated parts of a system increases the risk of implementing solutions that may be inefficient by overlooking dynamic and aggregated effects that emerge at larger scales [40]. This may result in overestimation of the effectiveness of NBS but also in insufficiency to assess circularity of complex systems.

The answer to view the two concepts through the same lens may be seen in the increasing acknowledgement that the transition towards circularity requires the consideration of a territorial dimension [41]. This means that CE materialises in different ways depending on local needs, local resources, and local conditions. Therefore, any territory should be seen as a system consisting of human-managed and nature-managed sub-systems, where specific socio-economic activities, regulatory actors, public/consumer behaviour, habits, and preferences take place and directly or indirectly affect (and are affected by) the natural environment.

Based on this approach, analysis of the local context would indicate the state of the local natural environment and capital, where the focus should be put on to achieve regeneration, which resources, materials, and products are of major importance to close their loops, and specific waste externalities that require management. The NBS for implementation to address the local issues should be assessed by their effectiveness in achieving these goals based on the local context. Therefore, the circularity targets are always the same (i.e., the three principles) but the factors that affect these goals change based on the local conditions, and these factors can be measured and communicated using relevant indicators.

Currently, a wide set of indicators exists in literature covering most of the aspects of circularity. However, the existence of numerous indicators does not necessarily mean that they are capable of adequately and holistically measure circularity in complex systems. For example, Nika *et al.* [42] developed a list of circularity performance indicators (CPI) targeted at the three CE principles, ensuring the consideration of all circularity aspects. The CPI consist of nine indicators targeted at the regeneration of natural capital, covering aspects of natural water cycle, water quality, nutrient balance, soil, biodiversity, land cover, and economic revenues/savings; five indicators measuring the principle of keep resources in use focusing on circular flow, circular use, and economic benefits; and five indicators evaluating the principle of design out waste externalities by measuring waste and emissions.

The methods used to calculate the indicators are various from the more common Material Flow Analysis (MFA), Life Cycle Assessment (LCA), and economic valuation methods, to more complex modelling tools (hydraulic, hydrological, agro-hydrological, hydro-biogeochemical models, etc.) and other more resource-intensive tools (quality measurements, biological samplings, surveys, satellite images, etc.) to predict complex system behaviour, emerging from non-linearities, time lags, and unexpected results caused by feedback loops. Similar sets of indicators should be adopted and used for the assessment of both NBS and circularity in cities and other territories based on their local conditions and needs.

Conclusions

Circular management of resources in cities is crucial for addressing global environmental problems. Circular economy is viewed as a mechanism that helps cities to shift from linear to circular resource management. The major identified urban challenges, i.e., UCC in this transition, are as follows: (1) restoring and maintaining the water cycle; (2) water and waste treatment, recovery, and reuse; (3) nutrient recovery and reuse; (4) material recovery and reuse; (5) food and biomass production; (6) energy efficiency and recovery; and (7) building system recovery. Implementing NBS in cities can address these challenges as NBS provide multiple benefits and they are multifunctional. Moreover, the proposed NBS circular framework is a first step towards a better understanding of a much needed systematic view of urban landscapes in which NBS units and interventions can interact with other urban chains ensuing that UCC are properly addressed. Finally, the relevance of circularity assessment has been introduced. Because the current approach to CE focuses mainly on manufactured products and their related economic activities, NBS struggle to find their position within the concept of CE, and the benefits they provide are rarely assessed from a circularity perspective. Recent developments in providing a list of CPI targeted at the three CE principles were presented.

Code Availability N/A

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Data Availability N/A

Declarations

Conflict of Interest The authors declare that there is no conflict of interest.

References

1. Murray A, Skene K, Haynes K (2017) The circular economy: an interdisciplinary exploration of the concept and application in a global context. J Bus Ethics 140:369–380. https://doi.org/10.1007/s10551-015-2693-2
2. Babbitt CW, Gaustad G, Fisher A, Chen WQ, Liu G (2018) Closing the loop on circular economy research: from theory to practice and back again. Resour Conserv Recycl 135:1–2. https://doi.org/10.1016/j.resconrec.2018.04.012
3. Hofmann F (2019) Circular business models: business approach as driver or obstructer of sustainability transitions? J Clean Prod 224:361–374. https://doi.org/10.1016/j.jclepro.2019.03.115

4. Ellen MacArthur Foundation (2015) Delivering the circular economy: a toolkit for policymakers. https://www.ellenmacarthurfoundation.org/publications
5. Raymond CM, Frantzeskaki N, Kabisch N, Berry P, Breil M, Nita MR, Geneletti D, Calfapietra C (2017) A framework for assessing and implementing the co-benefits of nature-based solutions in urban areas. Environ Sci Pol 77:15–24. https://doi.org/10.1016/j.envsci.2017.07.008
6. Pearlmutter D, Theochari D, Nehls T, Pinho P, Piro P, Korolova A, Papaefthimiou S, Mateo MCG, Calheiros C, Zluwa I, Pitha U, Schosseler P, Florentin Y, Ouannou S, Gal E, Aicher A, Arnold K, Igondová E, Pucher B (2020) Enhancing the circular economy with nature-based solutions in the built urban environment: green building materials, systems and sites. Blue-Green Syst 2(1):46–72
7. Oral HV, Carvalho P, Gajewska M, Ursino N, Masi F, Hullebusch ED, Kazak JK, Exposito A, Cipolletta G, Andersen TR, Finger DC, Simperler L, Regelsberger M, Rous V, Radinja M, Buttiglieri G, Krzeminski P, Rizzo A, Dehghanian K, Nikolova M, Zimmermann M (2020) State of the art of implementing nature based solutions for urban water utilization towards resourceful circular cities. Blue-Green Syst 2(1):112–136
8. Kisser J, Wirth M, De Gusseme B et al (2020) A review of nature-based solutions for resource recovery in cities. Blue-Green Syst 2(1):138–172
9. Skar SLG, Pineda-Martos R, Timpe A, Pölling B, Bohn K, Külvik M, Delgado C, Pedras CMG, Paço TA, Ćujić M, Tzortzakis N, Chrysargyris A, Peticila A, Alencikiene G, Monsees H, Junge R (2020) Urban agriculture as an innovative mechanism to secure cities a sustainable and healthy development in the future. Blue-Green Syst 2(1):1–35
10. Katsou E, Nika CE, Buehler D et al (2020) Transformation tools enabling the implementation of nature-based solutions for creating a resourceful circular city. Blue-Green Syst 2(1):186–211
11. Langergraber G, Pucher B, Simperler L, Kisser J, Katsou E, Buehler D, Garcia Mateo MC, Atanasova N (2020) Implementing nature-based solutions for creating a resourceful circular city. Blue-Green Syst 2(1): 173–185. https://doi.org/10.2166/bgs.2020.933
12. Andreucci MB (2018) Economic valuation of urban green infrastructure. Principles and evidence. Economics and Policy of Energy and the Environment, Ed. Franco Angeli, (2), pages 63-84.
13. Castellar JAC, Popartan A, Pueyo-Ros J, Atanasova N, Langergraber G, Corominas L, Comas J, Acuña V (2021) Nature-based solutions in the urban context: terminology, classification, and scoring for urban challenges and ecosystem services. Sci Total Environ 2021:146237. https://doi.org/10.1016/j.scitotenv.2021.146237
14. UNALAB (2019) Nature Based Solutions – Technical Handbook (Part II). https://unalab.eu/system/files/2020-02/unalab-technical-handbook-nature-based-solutions2020-02-17.pdf
15. NATURE4CITIES (2020) NBS multi-scalar and multi-thematic typology and associated database. Deliverable D1:1 retrieved from https://www.nature4cities.eu/results
16. Somarakis G, Stagakis S, Chrysoulakis N, (2019) Editors ThinkNature Nature Based Solutions Handbook. ThinkNature project funded by the EU Horizon 2020 research and innovation programme under grant agreement No. 730338, 226p. https://doi.org/10.26225/jerv-w202
17. URBANGREENUP (2018) NBS Catalogue: Deliverable D1.1; https://www.urbangreenup.eu/insights/
18. Castellar JAC, Arias CA, Carvalho P, Rysulova M, Pérez G, Bosch M, Morato J (2018) WETWALL - an innovative design concept for the treatment of wastewater at an urban scale. Desalin Water Treat 109:205–220. https://doi.org/10.5004/dwt.2018.22143
19. Nelson VI (2008) New approaches in decentralized water infrastructure. Coalition for Alternative Wastewater Treatment. Glouchester, MA 01930. https://decentralizedwater.waterrf.org/documents/04-dec-5sg/04dec5report.pdf
20. Capodaglio AG, Callegari A, Cecconet D, Molognoni D (2017) Sustainability of decentralized wastewater treatment technologies. Water Pract Technol 12(2):463–477. https://doi.org/10.2166/wpt.2017.055
21. Mengke P, Zhang B, He Y, Su J, Gin K, Lev O, Shen G, Hu S (2019) State of the art of tertiary treatment technologies for controlling antibiotic resistance in wastewater treatment plants. Environ Int 131:105026. https://doi.org/10.1016/j.envint.2019.105026
22. Svete LE (2012) Vegetated greywater treatment walls: design modifications for intermittent media filters. Norwegian University of Life Sciences
23. Masi F, Bresciani R, Rizzo A, Edathoot A, Patwardhan N, Panse D, Langergraber G (2016) Green walls for greywater treatment and recycling in dense urban areas: a case-study in pune. J Water Sanit Hyg Dev 6(2): 342–347. https://doi.org/10.2166/washdev.2016.019
24. Fowdar H, Hatt BE, Breen P, Cook PLM, Deletic A (2017) Designing living walls for greywater treatment. Water Res 110:218–232. https://doi.org/10.1016/j.watres.2016.12.018
25. Azkorra Z, Pérez G, Coma J, Cabeza LF, Bures S, Álvaro JE, Erkoreka A, Urrestarazu M (2015) Evaluation of green walls as a passive acoustic insulation system for buildings. Appl Acoust 89:46–56. https://doi.org/10.1016/j.apacoust.2014.09.010
26. Natarajan M, Rahimi M, Sen S, Mackenzie N, Imanbayev Y (2015) Living wall systems: evaluating life-cycle energy, water and carbon impacts. Urban Ecosyst 18:1–11. https://doi.org/10.1007/s11252-014-0378-8

27. Manso M, Castro-Gomes J, Silva PD (2013) Modular system design for vegetated surfaces: a proposal for energy-efficient buildings. BESS-SB13 CALIFORNIA: Advancing Towards Net Zero. Pomona, California, USA. (June), 1–6.
28. Castellar JAC, Formosa J, Fernández AI, Jové P, Bosch MG, Morató J, Brix H, Arias CA (2019a) Cork as a sustainable carbon source for nature-based solutions treating hydroponic wastewaters - preliminary batch studies. Sci Total Environ 650:267–276. https://doi.org/10.1016/j.scitotenv.2018.08.365
29. Wolcott S, Martin P, Goldowitz J, Sadeghi S (2016) Performance of green wall treatment of brewery wastewater. Environ Prot Eng 42(4):137–149. https://doi.org/10.5277/epe160411
30. Prodanovic V, Mccarthy D, Hatt B, Deletic A (2019) Designing green walls for greywater treatment: the role of plants and operational factors on nutrient removal. Ecol Eng 130:184–195. https://doi.org/10.1016/j.ecoleng.2019.02.019
31. Castellar JAC, Formosa J, Chimenos JM, Canals J, Bosch M, Rosell JR, da Silva HP, Morató J, Brix H, Arias CA (2019b) Crushed autoclaved aerated concrete (CAAC), a potential reactive filter medium for enhancing phosphorus removal in nature-based solutions-preliminary batch studies. Water 11(7). https://doi.org/10.3390/w11071442
32. Gordillo N (2020) El campus de Sevilla, el primero en el mundo en conseguir la certificación medioambiental Leed Platino. Loyola and News – Diario de la Universidad Loyola Andalucía. Retrieved from http://www.loyolaandnews.es/el-campus-de-sevilla-de-loyola-el-primero-del-mundo-en-tener-la-certificacion-medioambiental-leed-platino/?fbclid=IwAR0Rlqced_lUjSOjETuLaat4RJs8UEhRlUfJJafXSqlYcPm1SOrw751L7zE
33. Torrejón O (2020) Campus Universidad Loyola, Dos Hermanas: Arquitectura del siglo XXI – luis vidal + arquitectos. Promateriales de construcción y arquitectura actual 139(2):88–99 Retrieved from https://promateriales.com/pdf/PM-139%205-min.pdf
34. Nearly Zero Energy Hotels (neZEH) (2016) Towards nearly zero energy hotels. Lighthouse examples: Boutiquehotel Stadthalle, Vienna, Austria. Retrieved from https://ec.europa.eu/energy/intelligent/projects/en/projects/nezeh and http://www.nezeh.eu/assets/media/PDF/Stadthalle_AT_factsheet60.pdf
35. Enzi V, Cameron B, Dezsényi P, Gedge D, Mann G, Pitha U (2017) Nature-based solutions and buildings – the power of surfaces to help cities adapt to climate change and to deliver biodiversity. In: Kabisch N, Korn H, Stadler J, Bonn A (eds) Nature-based solutions to climate change adaptation in urban areas, theory and practice of urban sustainability transitions. Springer, Cham. https://doi.org/10.1007/978-3-319-56091-5_10
36. Brandenburg C, Damyanovic D, Reinwald F, Allex B, Gantner B, Czachs C (2018) Urban heat island strategy – City of Vienna. Vienna Environmental Protection Department. Retrieved from: https://www.wien.gv.at/umweltschutz/raum/pdf/uhi-strategieplan-englisch.pdf
37. European Commission (2020) A new Circular Economy Action Plan - For a cleaner and more competitive Europe. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0098&from=EN
38. European Commission (2019) The European Green Deal. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52019DC0640&from=EN
39. Nika CE, Gusmaroli L, Ghafourian M, Atanasova N, Buttiglieri G, Katsou E (2020a) Nature-based solutions as enablers of circularity in water systems: a review on assessment methodologies, tools and indicators. Water Res 183:115988. https://doi.org/10.1016/j.watres.2020.115988
40. Thorslund J, Jarsjo J, Jaramillo F, Jawitz JW, Manzoni S, Basu NB, Chalov SR, Cohen MJ, Creed IF, Goldenberg R, Hylin A, Kalantari Z, Koussis AD, Lyon SW, Mazi K, Mard J, Persson K, Pietro J, Prieto C, Quin A, van Meter K, Destouni G (2017) Wetlands as large-scale nature-based solutions: status and challenges for research, engineering and management. Ecol Eng 108:489–497. https://doi.org/10.1016/j.ecoleng.2017.07.012
41. Bacova M, Bohme K, Guitton M, Herwijnen M V, Kallay T, Koutsomarkou J, Rok A, (2016) Pathways to a circular economy in cities and regions. ESPON, Policy Briefs. https://www.espon.eu/circular-regions#
42. Nika CE, Vasilaki V, Expósito A, Katsou E (2020b) Water cycle and circular economy: developing a circularity assessment framework for complex water systems. Water Res 187:116423. https://doi.org/10.1016/j.watres.2020.116423

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