Chapter 28
Implementing Nature-Based Solutions for a Circular Urban Built Environment

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Abstract This short review outlines the implementation of nature-based solutions in the urban built environment which can contribute to a circular economy as well as the multiple benefits related to the ecosystem services they can provide. The novel Circular City framework on the mainstreaming of nature-based solutions for

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the enhancement of urban resource management, which was developed within the COST Action CA17133, is presented. Urban circularity challenges addressed by nature-based solutions are assessed in the built environment following three different levels of implementation—i.e., green building materials, systems for the greening of buildings envelope, and green building sites as vegetated open spaces and water-sensitively designed. Considering the possibilities of implementing nature-based solutions in the built environment, we also highlight the circularity processes that can take place through the integration of nature-based solutions at some or all of the proposed scales towards the achievement of at least one of the seven urban circularity challenges. A collection of representative actual case studies exemplifying the development and implementation of nature-based solutions towards circular cities is also included.

Keywords Nature-based solutions · Circular economy · Built environment

28.1 Introduction

As defined by Langergraber et al. [1, 2], nature-based solutions (NBS) are approaches that not only bring nature into cities but also contribute towards solving or mitigating environmental and societal problems. In many cases, this includes ideas for urban design that are inspired or derived from nature [3]. The specific focus of this short review is to present the advances on the implementation of NBS within urban ecosystems—i.e., the built environment, towards Circular Economy (CE), which were proposed within the COST Action CA17133 Circular City: Implementing nature-based solutions for creating a resourceful circular city (2018–2023) [4].

Beside performing their specific and nominal intended design and use—such as water management (e.g., urban drainage), air quality, greening of the city, … —introducing or enhancing NBS within existing urban infrastructure provides multiple benefits, such as climate change mitigation and adaptation, reduction of the urban heat island effect (e.g., via evaporative cooling), wastewater treatment, while enhancing

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human wellbeing and liveability of cities [5], as well as biodiversity, and resource recovery [6]. All these aspects find expression in the design of urban spaces and buildings—what is concerned to as the built environment [3].

Over the last fifteen years, the concept of NBS appears to encompass contemporary landscapes and architecture design solutions, where natural and living materials—as well as policies strategies, measures and actions on participatory planning and governance promoting their applications—are leveraged to come across societal challenges posed by the urban built environment [3, 6, 7]. The urban green infrastructure and the related NBS are connected to the reduction of these issues, interconnected with physical phenomena occurring in cities [3, 6].

Another significant aspect when managing contemporary urban systems is the concept of circularity. Adopting the Circular Economy (CE) model constitutes an evolving umbrella representing multiple definitions and internal complexities, such as the one introduced by Langergraber et al. [1] as an economic system that aims at minimizing waste and making the most of resources (water, nutrients, materials, food, energy) by keeping these in circulation and reprocessing within the city [7]. In a circular system, resource inputs and outputs (as waste or emissions), as well as energy loss are minimized by closing and optimizing material cycles and energy cascades, including their economic and environmental efficiency [2, 7, 8].

This paper describes the urban challenges related to circularity that can be addressed through NBS, and the pathways and case studies on how NBS can be included in the built environment [2, 7, 8].

28.1.1 Urban Circularity Challenges

To comply with the principles of CE, substantial amendments in the infrastructures' management and design along with promoting new or hybrid systems are needed by applying a multisectoral and multidisciplinary approach [7, 8]. NBS encompass an extraordinary potential to address several urban challenges and generate multiple co-benefits while delivering several ecosystem services.

A set of seven urban circularity challenges (UCCs) that can be addressed with NBS was postulated by Atanasova et al. [7].

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.

28.1.2 The Circular City Framework

The Circular City Framework, as defined by Langergraber et al. [2], aims at mainstreaming the use of NBS in urban environment. It is a framework for addressing UCCs with implementation of NBS, and includes:

- The updated definitions of all NBS that clear up hitherto confusing and overlapping terminology in this area;
- The catalogue of technologies for providing/recovering resources with NBS that comprises a set of 39 NBS units (NBS_u), 12 NBS interventions (NBS_i), and 10 Supporting units (S_u);
- The analysis of input and output (I/O) resource streams required for NBS units and interventions (NBS_u/i); and,
- A guidance tool—as a decision support system for the NBS implementation in cities.

28.2 Levels of Implementation

Pearlmutter et al. [3] proposed a series of different scales for NBS implementation in the built environment:

- **Green building materials**: They result from organic materials extracted from low environmental impacts biological cycle—e.g., water, carbon, and energy; in constructing the built environment [3]. It is considered a beneficial reuse of other resource streams to prevent harmful residues and guarantee a user-friendly living environment concerning indoor air quality and climate [3, 8]. Ideally, the material processing cycle should be designed to circle back the nutrients safely to the ecosystem at the end of its usage cycle [3, 8].
- **Green building systems**: These include green building-integrated systems such as extensive and intensive green roofs (GRs), vertical greening systems (VGSs), house trees, building integrated treatment wetlands, and building integrated agriculture (BIA) [2, 3, 8–11]; to optimize, among others, the energy efficiency of the buildings:
  - *Green roofs:* systems that are implemented on a constructed structure comprising several layers, playing different functions, with vegetation on top.
  - *Vertical greening systems:* consist of vegetation planted in soil or in artificial or organic substrates as part of suspended panels on the wall surface where plants are grown.
  - *House trees:* are planted next to or within the building infrastructure – for instance, Bosco Verticale in Milan and Hundertwasser Haus in Vienna. Such traditional European features of buildings notably influence the buildings' energy efficiency, thanks to the cast shadow in summer and light pass during wintertime.

  - *Building integrated treatment wetlands*: are systems designed to collect and hold rain runoff or to treat wastewater from the building with high pollutant removal efficiency. If designed properly, GRs and VGSs can also function as treatment wetlands and treat rainwater or greywater [9, 10, 12, 13].
  - *Building integrated agriculture*: is a practice to synergize the built environment and agriculture [11, 14]. The result are mixed-use buildings with a farming system, using the local source of water and energy to produce food. It is possible to integrate a rooftop greenhouse with the building below, and thus optimize the metabolism of the building (cooling/heating and gas exchange (CO_2/O_2)) [15].

- **Green building sites**: these may be open land spaces or parcels next to the buildings that offer spaces for establishing nature in cities and provide multiple ecosystem services**.** Such spaces could be essential in the management of urban blue-green infrastructure and water resources [2, 3, 8, 9].

Following their approach [3], we consider these three scales of implementation—i.e., from the building materials, systems for the greening of buildings, and green urban sites (Fig. 28.1) in subsequent analyses [9, 16].

Fig. 28.1 Nature-based solutions' scales of implementation in the built environment: green building materials, systems, and sites; and associated urban circularity challenges

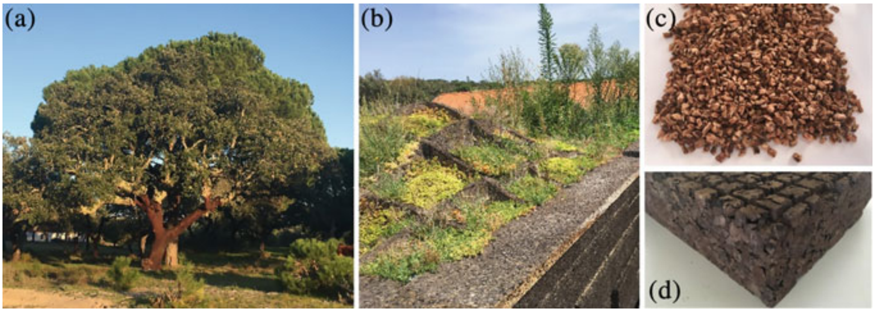

Fig. 28.2 Green roofs and cork as green building material: **a** cork oak tree; **b** cork green roof; **c** granulated cork; and **d** insulation cork board. Original images from Calheiros, C. S. C

28.3 Case Studies

28.3.1 *Cork as Green Building Material for Green Roof Systems*

The interest in materials considered to optimize GRs' structural layers performance at the building level, as delivering different services and promoting circularity of the built environment is rising [17].

Cork is the bark of the cork oak tree (*Quercus suber* L.) which is periodically harvested from the trees (Fig. 28.2a); and it has been long used in the built environment—mainly due to its capacity of thermal and acoustic insulation. More recently, it has been tried as a component of NBS [17, 18]. Its application has been considered in GRs' systems (Fig. 28.2b) as a component of the substrate (Fig. 28.2c) as well as drainage and protection layer (Fig. 28.2d).

Granulated cork was selected as main substrate component by Monteiro et al. [19] because of its low weight and good capacity for water adsorption, being also adequate for plant establishment. Moreover, as water drainage and protection layer, the insulation cork board has the potential to replace conventional synthetic materials—e.g., extruded polystyrene [20]; and thus, contribute towards negative carbon footprint.

The sustainability of materials deployed in GRs still needs to improve. Life cycle and carbon footprint assessments can support and highlight the best direction [20, 21].

28.3.2 *Vertical Greening Systems for Indoor Air Quality Using Recycled Substrates*

VGSs are increasingly adopted as a nature-based strategy to improve air quality in interiors. Many investigations demonstrated potential of air phytoremediation in ornamental plant species on main indoor air pollutants [22, 23]. Other studies focused on the importance of growing media composition specially to increase the efficiency of active botanical biofiltration of volatile organic compounds (VOCs) [24]. Despite the importance of cultivation substrate for functional VGSs, scant research is carried out to assess the influence of alternative growing media produced with recycled components on the indoor phytoremediation efficiency.

Organic-rich substrate along with coconut fiber, perlite and vermicompost, obtained from by valorization of organic waste, showed promising results as growing medium for VGSs and contributed to improved indoor air quality [25]. De Lucia et al. [26] obtained good prospects when testing the influence of recycled rice husk-based substrate in modular VGSs on plant health status and thermal comfort.

Focusing on innovation and production of alternative growing media, recycled organic and inorganic by-products and waste derived from local supply chains, can be a promising way to increase circularity and improve the sustainability of VGSs.

28.3.3 Vertical Greening Systems for Greywater Treatment

The use of treated greywater can contribute to restoring and recreating the hydrological cycle in a circular and sustainable way; as well as the reuse and recovery of nutrients in urban environments [7, 9]. Sustainable water management in cities can be addressed through the implementation of potential NBS, such as the case of VGSs; providing, in addition to circularity strategies, additional benefits for the inhabitants and their environment [2, 7, 9].

Proper selection of plants and filter media used in a VGS play an essential role in maximizing the performance of greywater treatment. In addition, in these complex integrated treatment systems, both components influence water requirements, aesthetics, hygienic-sanitary conditions, and system maintenance; fundamental factors for the success of its large-scale implementation [12, 13].

The experimental system installed at BOKU University (Fig. 28.3) demonstrated its multifunctionality on a large scale by identifying its water demand, maximizing local thermal reduction by evapotranspiration [13]. Plants were evaluated for their adequacy to different irrigation conditions and types of water [13].

28.3.4 Building Integrated Agriculture, the Case of Rroofood Project

In climates with dry, hot summers, GRs microclimate can be very harsh for plants; and use of locally adapted wild plants present a solution of increasing agricultural production in urban environments.

Fig. 28.3 Vertical greening system at the University of Natural Resources and Life Sciences Vienna (BOKU), Vienna, Austria. The system has a total size of 6m x 4m and consists of four individual systems with their own irrigation system. Monitoring included air and substrate temperature, substrate water content, precipitation, solar radiation, irrigation water volume and system output [13]

The Rroofood project [27, 28] evaluated the suitability of wild edible plants to find enhanced sustainable production solutions for urban farming in GRs. A collection of plant species was sown in a GR at Instituto Superior de Agronomia (Universidade de Lisboa, Portugal) campus (Fig. 28.4), with the selected following three criteria: (i) used in traditional gastronomy; (ii) from areas with environmental conditions of equal or greater demand than the Lisbon area; and (iii) species with resilience traits. Such traits minimize the need for external resource inputs such as water and energy, fertilizers and pesticides.

Fifteen species from the genera *Amaranthus*, *Beta*, *Cakile*, *Chenopodium*, *Chrysanthemum*, *Nigella*, *Papaver*, *Petroselinum*, *Rumex*, *Scolymus*, *Tragopogon*, and *Viola* were selected. Most of these germinated and developed successfully. Two species reseeded naturally and another group of four was still present in the next spring. From those, a selection of five species with potentially interesting features, combining plant physiology traits and gastronomic aptitude, for further work, was made [27].

Fig. 28.4 **a** Green roof built at the Instituto Superior de Agronomia campus—as part of *the green roof lab*, Universidade de Lisboa, Portugal; **b** detail of *Nigella damascena* plant. Original images from Paço, T. A

28.4 Conclusions

The search for less energy intensive and resource-demanding, and thus more CO_2-neutral solutions for societal challenges has been intensified recently—having in consideration the alignment of the European policies and strategies and the global policies related to the United Nations Agenda 2030 and The Paris Agreement. The present short paper aims to highlight potential contributions of nature-based solutions to the development of COST Action CA21103 CircularB framework of a circularity rating tool build from the state-of-the-art and best practices of circular economy in the construction of the built environment, coupled with the European Union Circular Economy Action Plan. Several case-studies are presented, at the level of green building-integrated systems, illustrating the potential of nature-based solutions to cope with circularity processes, either via structures or materials, towards a circular urban built environment.

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