














Chapter 28

Implementing Nature-Based Solutions for a Circular Urban Built Environment



Rocío Pineda-Martos , Nataša Atanasova , Cristina S. C. Calheiros , Ranka Junge , Samaneh S. Nickayin , Teresa A. Paço , Laura Dominici , Elena Comino , Maria-Beatrice Andreucci , Dimitra Theochari, Bernhard Pucher , Aránzazu Galán González , Pedro N. Carvalho , and Guenter Langergraber 

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

R. Pineda-Martos (✉)

University of Seville, School of Agricultural Engineering, Urban Greening and Biosystems Engineering Research Group (ETSIA-US), Ctra. de Utrera, Km.1, 41013 Seville, Spain
e-mail: rpineda@us.es

N. Atanasova

University of Ljubljana, Faculty of Civil and Geodetic Engineering, Jamova Cesta 2, 1000 Ljubljana, Slovenia

C. S. C. Calheiros

Interdisciplinary Centre of Marine and Environmental Research (CIIMAR/CIMAR), University of Porto, Novo Edifício Do Terminal de Cruzeiros Do Porto de Leixões. Avenida General Norton de Matos S/N, 4450-208 Matosinhos, Portugal

R. Junge

Zurich University of Applied Sciences, Institute of Natural Resource Sciences, Grüental 14, 8820 Wädenswil, Switzerland

S. S. Nickayin

Agricultural University of Iceland, Faculty of Planning and Design, 311 Borgarbyggð, Hvanneyri, Iceland

T. A. Paço

Universidade de Lisboa, Instituto Superior de Agronomia, LEAF—Linking Landscape, Environment, Agriculture and Food Research Center, Associated Laboratory TERRA, Tapada da Ajuda, 1349-017 Lisboa, Portugal

L. Dominici · E. Comino

Politecnico Di Torino, Department of Environment, Land and Infrastructure Engineering, Corso Duca Degli Abruzzi 24, 10129 Turin, Italy

M.-B. Andreucci

Sapienza University of Rome, Faculty of Architecture, Via Flaminia 72, 00196 Rome, Italy

© The Author(s) 2024

L. Bragança et al. (eds.), *Creating a Roadmap Towards Circularity in the Built Environment*, Springer Tracts in Civil Engineering, https://doi.org/10.1007/978-3-031-45980-1_28

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

D. Theochari

MERA Landschaftsarchitekten mbB, Griegstraße 75, Haus 24B, 22763 Hamburg, Germany

B. Pucher · G. Langergraber

University of Natural Resources and Life Sciences Vienna (BOKU), Department of Water, Atmosphere and Environment, Institute of Sanitary Engineering, Muthgasse 18, 1190 Vienna, Austria

A. G. González

Université Libre de Bruxelles, Department of Building, Architecture and Town Planning, Avenue Franklin Roosevelt 50, 1050 Brussels, Belgium

P. N. Carvalho

Aarhus University, Department of Environmental Science, Frederiksborgvej 399, 4000 Roskilde, Denmark

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 (CO₂/O₂)) [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].

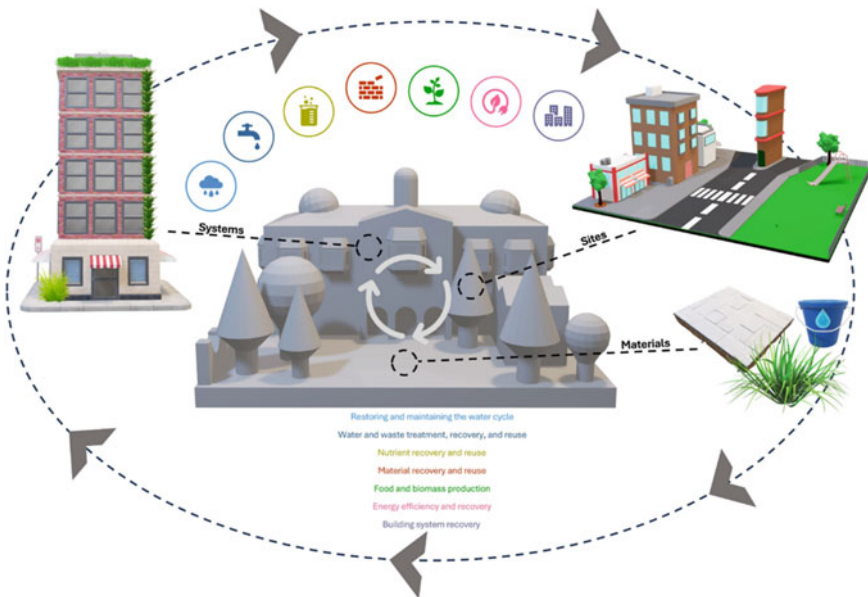


Fig. 28.1 Nature-based solutions’ scales of implementation in the built environment: green building materials, systems, and sites; and associated urban circularity challenges

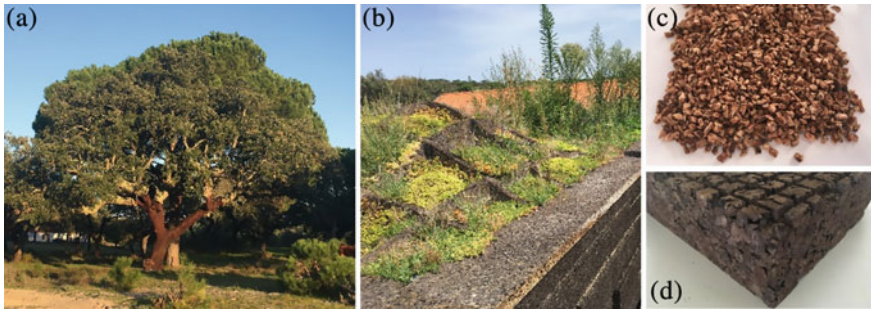


Fig. 28.2 Green roofs and cork as green building material: **a** cork oak tree; **b** cork green roof; **c** granulated cork; and **d** insulation cork board. Original images from Calheiros, C. S. C

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 Rooftop 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 Rooffood 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 CO₂-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.

Acknowledgements The authors are grateful for the support from the COST Action CA17133 Circular City, <https://circular-city.eu/>. C.C.S.C. is thankful to Fundação para a Ciência e Tecnologia (FCT) regarding UIDB/04423/2020 and UIDP/04423/2020 projects.

References

1. 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 Systems* 2(1):173–185
2. Langergraber G, Castellar JAC, Pucher B, Baganz GFM, Milosevic D, Andreucci M-B, Kearney K, Pineda-Martos R, Atanasova N (2021) A framework for addressing circularity challenges in cities with nature-based solutions. *Water* 13(17):2355
3. Pearlmutter D, Theochari D, Nehls T, Pinho P, Piro P, Korolova A, Papaefthimiou S, Garcia Mateo MC, 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 Systems* 2(1):46–72
4. COST Action CA17133 Circular City - Implementing nature-based solutions for creating a resourceful circular city, <https://circular-city.eu/>, Last Accessed 2023/02/20
 5. de Haan FJ, Ferguson BC, Adamowicz RC, Johnstone P, Brown RR, Wong THF (2014) The needs of society: A new understanding of transitions, sustainability and liveability. *Technol Forecast Soc Chang* 85:121–132
 6. Pineda-Martos R, Calheiros CSC (2021) Nature-based solutions in cities—Contribution of the Portuguese National Association of Green Roofs to urban circularity. *Circ Econ Sustain* 1:1019–1035
 7. Atanasova N, Castellar JAC, Pineda-Martos R, Nika CE, Katsou E, Istenič D, Pucher B, Andreucci MB, Langergraber G (2021) Nature-based solutions and circularity in cities. *Circ Econ Sustain* 1:319–332
 8. Langergraber G, Castellar JAC, Andersen TR, Andreucci M-B, Baganz GFM, Buttiglieri G, Canet-Martí A, Carvalho PN, Finger DC, Griessler Bulc T, Junge R, Megyesi B, Milošević D, Oral HV, Pearlmutter D, Pineda-Martos R, Pucher B, van Hullebusch ED, Atanasova N (2021) Towards a cross-sectoral view of nature-based solutions for enabling circular cities. *Water* 13(17):2352
 9. Pearlmutter D, Pucher B, Calheiros CSC, Hoffmann KA, Aicher A, Pinho P, Stracqualursi A, Korolova A, Pobric A, Galvão A, Tokuç A, Bas B, Theochari D, Milosevic D, Giancola E, Bertino G, Castellar JAC, Flaszynska J, Onur M, Garcia Mateo MC, Andreucci MB, Milousi M, Fonseca M, Di Lonardo S, Gezik V, Pitha U, Nehls T (2021) Closing water cycles in the built environment through nature-based solutions: The contribution of vertical greening systems and green roofs. *Water* 13(16):2165
 10. Cross K, Tondera K, Rizzo A, Andrews L, Pucher B, Istenič D, Karres N, McDonald R (eds) (2021) Nature-based solutions for wastewater treatment: A series of factsheets and case studies. IWA Publishing, London, United Kingdom
 11. Caplow T (2009) Building integrated agriculture: Philosophy and practice. In: *Urban futures 2030: Urban development and urban lifestyles of the future*, pp 48–51. Herausgegeben von der Heinrich-Böll-Stiftung, Berlin, Germany
 12. Pradhan S, Al-Ghamdi SG, Mackey HR (2019) Greywater recycling in buildings using living walls and green roofs: A review of the applicability and challenges. *Sci Total Environ* 652:330–344
 13. Pucher B, Zluwa I, Spörl P, Pitha U, Langergraber G (2022) Evaluation of the multifunctionality of a vertical greening system using different irrigation strategies on cooling, plant development and greywater use. *Sci Total Environ* 849:157842
 14. Gould D, Caplow T (2012) Building-integrated agriculture: A new approach to food production. In: *Metropolitan sustainability*, pp 147–170. Woodhead Publishing
 15. Pons O, Nadal A, Sanyé-Mengual E, Llorach-Massana P, Cuerva E, Sanjuan Delmàs D, Muñoz P, Oliver-Solà J, Planas C, Rovira MR (2015) Roofs of the future: rooftop greenhouses to improve buildings metabolism. *Procedia Eng* 123:441–448
 16. Canet-Martí A, Pineda-Martos R, Junge R, Bohn K, Paço TA, Delgado C, Alenčičienė G, Skar SLG, Baganz GFM (2021) Nature-based solutions for agriculture in circular cities: Challenges, gaps, and opportunities. *Water* 13(18):2565
 17. Calheiros CSC, Stefanakis AI (2021) Green roofs towards circular and resilient cities. *Circ Econ Sustain* 1:395–411
 18. Talhinhas P, Ferreira JC, Ferreira V, Soares AL, Espírito-Santo D, do Paço TA (2023) In the search for sustainable Vertical Green Systems: An innovative low-cost indirect green façade structure using Portuguese native ivies and cork. *Sustain* 15, 5446
 19. Monteiro CM, Calheiros CSC, Martins JP, Costa FM, Palha P, de Freitas S, Ramos NMM, Castro PML (2017) Substrate influence on aromatic plant growth in extensive green roofs in a Mediterranean climate. *Urban Ecosyst* 20:1347–1357

20. Carbon footprint of the insulation cork board (2017) Tártaro A. S., Mata, T. M., Martins A. A., Esteves da Silva, J. C. G. *J Clean Prod* 143:925–932
21. Tams L, Nehls T, Calheiros CSC (2022) Rethinking green roofs- natural and recycled materials improve their carbon footprint. *Build Environ* 219:109122
22. Kim KJ, Shagol CC, Torpy FR, Pettit T, Irga PJ (2020) Plant physiological mechanisms of air treatment. In: Soreanu, G., Dumont, E. (eds.) *From biofiltration to promising options in gaseous fluxes biotreatment—Recent developments, new trends, advances, and opportunities*, pp 219–244. Elsevier
23. Mata TM, Martins AA, Calheiros CSC, Villanueva F, Alonso-Cuevilla NP, Fonseca Gabriel M, Ventura Silva G (2022) Indoor air quality: A review of cleaning technologies. *Environ* 9:118
24. Pettit T, Irga PJ, Surawski NC, Torpy FR (2019) An assessment of the suitability of active green walls for NO₂ reduction in green buildings using a closed-loop flow reactor. *Atmos* 10(12):801
25. Kazemi F, Rabbani M, Jozay M (2020) Investigating the plant and air-quality performances of an internal green wall system under hydroponic conditions. *J Environ Manage* 275:111230
26. De Lucia M, Treves A, Comino E (2021) Rice husk and thermal comfort: Design and evaluation of indoor modular green walls. *Dev Built Environ* 6:100043
27. do Paço TA, Arsénio P, Pinto da Costa F, Raymundo A, Prista C, Magalhães A, Espírito-Santo D (2022) The wild food rooftop—Traditional edible plants in a green roof of Lisbon area. In: *International Web Conference on Food Choice and Eating Motivation*, 19–20 May. Online event
28. The Roofood project, <https://tapaco4.wixsite.com/rroofood>, Last Accessed 2023/02/20

Open Access This chapter is licensed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this chapter are included in the chapter's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.

