Circular Economy and Sustainability

Alexandros Stefanakis
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Nature-based Solutions for Circular Management of Urban Water

Springer

Circular Economy and Sustainability

This book series aims at exploring the rising field of Circular Economy (CE) which is rapidly gaining interest and merit from scholars, decision makers and practitioners as the global economic model to decouple economic growth and development from the consumption of finite natural resources. This field suggests that global sustainability can be achieved by adopting a set of CE principles and strategies such as design out waste, systems thinking, adoption of nature-based approaches, shift to renewable energy and materials, reclaim, retain, and restore the health of ecosystems, return recovered biological resources to the biosphere, remanufacture products or components, among others.

However, the increasing complexity of sustainability challenges has made traditional engineering, business models, economics and existing social approaches unable to successfully adopt such principles and strategies. In fact, the CE field is often viewed as a simple evolution of the concept of sustainability or as a revisiting of an old discussion on recycling and reuse of waste materials. However, a modern perception of CE at different levels (micro, meso, and macro) indicates that CE is rather a systemic tool to achieve sustainability and a new eco-effective approach of returning and maintaining waste in the production processes by closing the loop of materials. In this frame, CE and sustainability can be seen as a multidimensional concept based on a variety of scientific disciplines (e.g., engineering, economics, environmental sciences, social sciences). Nevertheless, the interconnections and synergies among the scientific disciplines have been rarely investigated in depth.

One significant goal of the book series is to study and highlight the growing theoretical links of CE and sustainability at different scales and levels, to investigate the synergies between the two concepts and to analyze and present its realization through strategies, policies, business models, entrepreneurship, financial instruments and technologies. Thus, the book series provides a new platform for CE and sustainability research and case studies and relevant scientific discussion towards new system-wide solutions.

Specific topics that fall within the scope of the series include, but are not limited to, studies that investigate the systemic, integrated approach of CE and sustainability across different levels and its expression and realization in different disciplines and fields such as business models, economics, consumer services and behaviour, the Internet of Things, product design, sustainable consumption & production, bio-economy, environmental accounting, industrial ecology, industrial symbiosis, resource recovery, ecosystem services, circular water economy, circular cities, nature-based solutions, waste management, renewable energy, circular materials, life cycle assessment, strong sustainability, and environmental education, among others.

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ISSN 2731-5509 ISSN 2731-5517 (electronic)
Circular Economy and Sustainability
ISBN 978-3-031-50724-3 ISBN 978-3-031-50725-0 (eBook)
https://doi.org/10.1007/978-3-031-50725-0

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Paper in this product is recyclable.

Contents

Chapter 1
Circular Cities Solution with Biophilic Design and Nature-Based Solutions

Makbulenur Onur and Cengiz Acar

Abstract Today, as a result of the increasing population, needs and deterioration in the supply/demand balance and the destructive effects of humans on nature have increased. Parallel to this result, it also caused the deterioration of the ecological balance. Human beings, who feel that they have control and power over nature, have disrupted the balance of nature over time and have become increasingly distant from nature in this deteriorated balance. Urban green spaces are struggling with many problems that can be described as "urban disease". The United Nations shows that the world population will reach approximately 10 billion in 2050. In response to these problems, innovative approaches are applied to design more livable, healthy, sustainable, and resilient cities. Biophilic design and nature-based solutions (NbS) are at the forefront of these approaches. Although both approaches are based on sustainability, their focus is different. One of the general objectives of our research is to evaluate the ecosystem services provided by urban green infrastructure in terms of biophilic design and nature-based solutions. The specific objectives of this research are (1) to compile monitoring and evaluation indicators for biophilic planning with biophilic design pioneers such as Wilson (Biophilia: the human bond with other species. Harvard University Press, Cambridge, 1984), Beatley (Biophilic cities: integrating nature into urban design and planning. Washington, DC, Island Press, 2010), (2) to determine how these parameters can be used to lead innovation through an expert survey, and (3) questioning how to improve health, well-being, and productivity in the built environment. It is foreseen that a method proposal can be developed to create sustainable cities, thanks to the findings obtained as a result of this research, expert surveys, and method diagram.

Keywords Circular cities · Biophilic design · NbS · Design with nature

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A. Stefanakis et al. (eds.), *Nature-based Solutions for Circular Management of Urban Water*, Circular Economy and Sustainability,
https://doi.org/10.1007/978-3-031-50725-0_1

1.1 Introduction

Mankind has changed the balance of nature in line with their own needs and demands. In order to restore this balance, many design approaches, policies, and so on provided many suggestions. In fact, the actor who breaks down and fixes in this process is "human being". Cities also play an important role in the realization of the concept of a sustainable or transformable city. In this context, the rapid increase in the rate of urbanization throughout the world negatively affects the carrying capacity of the natural environment. This drags cities into more negative conditions day by day.

In the twenty-first century, the world population rate is increasing day by day. Therefore, the demand for basic services such as energy, food, and water continues to rise. The demographic changes experienced due to the increase in the urban population and migration bring the expectations for the economical, efficient, and fair distribution of resources to the agenda of local actors more. According to the 2018 Intergovernmental Panel on Climate Change (IPCC) report, global climate change will cause irreversible damage to humans, the built environment, and the biosphere (IPCC 2015).

Urbanization is a physical and social process. How these processes develop is important. As a result of the industrial revolution, this process has revealed the concept called "urbanization". It has become a serious problem for underdeveloped or developing countries with the effect of the serious population increase in the twentieth century (Weber et al. 1958; Ateş et al. 2019). In the cities of the future, an amalgamation of challenges looms large, encompassing not solely the burgeoning population growth, pressing environmental concerns, the intricate conundrum of urban waste management, and the palpable depletion of finite resources, but also navigating through the intricate tapestry of a transforming social fabric catalyzed by the rapid evolution of information technologies. This confluence of circumstances has invariably spurred a heightened call for the adoption and implementation of ecological approaches to address these multifaceted issues.

The concept of sustainability says that ecological and human capital are worth protecting (Friedrich 2021). Wackernagel et al., in his study in 1999, say that the first of these purposes is the protection of the habitat. Heckman (2000) expresses the nature worth protecting as the sum of human knowledge and skills. This can be explained as being inspired by natural events (Wilson 1984). There are different views on how to protect sustainable life and ecological potential (Bjørn and Hauschild 2013; Ryberg et al. 2018; Friedrich 2021). These approaches do not mean that the ecology lost in nature is brought back in any way (Turner 1993).

1.2 From the Theory of Biophilia to Biophilic Design

Man's relationship with nature starts from the moment of biological existence and continues until his death. Nature is good for people physically and mentally (Beatley 2010; Hickman 2013; Kellert and Wilson 1993; Rohde and Kendle 1994; Ulrich 1984; Wilson 1984; Kellert and Calabrese 2015). Biophilic design, which is an advocating approach, first emerged as a concept and then took its place in space designs. It is an approach used even in urban planning today. The concept of biophilia, which was first introduced by psychologist Erich Fromm (1964), was defined as "passionate love for life and living things." Fromm (1964) argues that the connection between humans and nature is biologically registered (Fromm 1964). The biophilia hypothesis, which is a new concept in theory but based on the existence of human beings in practice, connects the physical and mental evolution of human beings to the natural elements around them.

Landscape designers use natural elements and topography to balance nature and the built environment, thus making urban environments more livable and attractive. This design approach is related to biophilic design. Biophilic design proposed by Wilson (1984) and Kellert et al. (2011) and others is a method of landscape architecture that includes natural elements such as trees, water and natural lines, and ecologies in the built environment. The basis of the work is to be inspired by nature and to solve the ecological problems that occur by being inspired by nature.

This design process is in two ways: (1) "organic or naturalistic," which refers to environmental features, natural shapes, forms, patterns, and processes and (2) "land based or local", which refers to and evolved from place-based relationships and human–nature relations (Kellert et al. 2008).

Kellert in his study conducted in 2010 discussed the nature of space under three main titles. These are direct experience of nature, indirect experience of nature, and experience of space and place. There are sub-parameters under the three main parameters. The main and sub-parameters are very important in the implementation/perception of biophilic design (Table 1.1).

Table 1.1 The 3 experiences and 24 attributes of biophilic design

Direct experience of nature	Indirect experience of nature	Experience of space and place
Light Air Water Plants Animals Weather Natural landscapes and ecosystems Fire	Images of nature Natural materials Natural colors Simulating natural light and air Naturalistic shapes and forms Evoking nature Information richness Age, change, and the patina of time Natural geometries Biomimicry	Prospect and refuge Organized complexity Integration of parts to wholes Transitional spaces Mobility and wayfinding Cultural and ecological attachment to place

The direct experience of nature expresses real contact with environmental features such as light, air, water, plants, animals, weather, natural landscapes and ecosystems, and fire in the built environment. It refers to the indirect experience of nature, representation or image of nature, transformation of nature, or exposure to certain patterns and processes that occur in nature. The experience of space and place refers to the characteristic spatial features of the natural environment that promote human health and well-being. Landscapes are spatial features such as shelter, integration of parts with the whole, mobility, and direction finding. The 24 biophilic design features identified in three categories are listed in Table 1.1 (Kellert 2018).

Biophilic design is about creating good habitats for humans as biological organisms in the built environment. Like all species, humans experience disruptions due to artificial forces. Biophilic design aims to satisfy these natural adaptations in the modern built environment and, in doing so, improve people's physical and mental health and wellness. The view that interacting with nature provides various psychological and physiological benefits to human health has been defended throughout history.

With the increase in urbanization in recent years, natural areas and natural elements have been replaced by manmade areas and mass production. This situation triggered more research on the relationship between man and nature by experts and led to the development of scientific studies. It has been accepted by expert employees that being together with nature has positive effects on human psychology; moreover, the view that watching nature, being close to an area that offers the opportunity to interact with nature, and knowing that it can be reached when desired provides psychological benefits to people as well as being in one-to-one contact with nature (Ulrich and Parsons 1992). When the pioneering studies on biophilic design are evaluated, the following explanations have been made on this term:

> Biophilic design is an attempt to translate the natural systems inherent in human beings with an understanding to relate to nature (Wilson 1984).

> Biophilic design is the planning of the inherent human need to relate to nature in the design of the built environment (Kellert et al. 2008).

> Biophilic design balances human needs with the value and considerations of natural environments and processes and incorporates the properties and qualities of these elements into architectural design (Dillon 2008).

The most important point that the supporters of the biophilic design emphasize is the human effort to survive in the evolutionary process, the success of production, and the bond they establish with life; this bond is valid as a feeling of closeness to nature and is a common feeling that every human has.

1.3 Biophilic Design and Nature-Based Solutions

Nature-based solution is basically a study to protect natural resources. In fact, it is an approach that evaluates new approaches and is inspired by nature (Fink 2016; Pearlmutter et al. 2021). At this point, biophilic design and nature-based solutions (NbS) intersect. Nature-based solutions use nature and find solutions to problems inspired by nature (Fig. 1.1). These solutions provide numerous benefits to the economy, society, and ecological systems. It is also defined as living solutions designed to address various environmental challenges, supported by natural processes and structures (European Commission 2016; Frantzeskaki 2019).

Therefore, the intersection of biophilic design approach and NbS is very important. Databases were analyzed in order to examine which studies included "biophilic design approach" and "NbS solutions" in scientific databases. Scopus and WOS were used to search for peer-reviewed, academic literature in the field of biophilic design and NbS. Figure 1.2 details the search methodology for this narrative review. A vast amount of sustainable literature was looked at for this review, which gives an overview of some of the key findings. It is not meant to be exhaustive but to provide an insight into the quality and quantity of evidence for each of the three biophilic experiences as found in the literature.

When the publications made under the keyword "biophilic design" in the Web of Science database were examined, it was determined that the main topic of 194 publications was biophilic design, and the highest rate between 2013 and 2022 was in 2022 (24.227%) (Fig. 1.3, Table 1.2).

Among the results obtained, the lowest rates were obtained between 2013 (1546%), 2014 (2062%), and 2015 (2577%). The increasing rate of results every year is among the important findings.

When the publications made under the keyword "Nature-based solutions (NbS)" in the Web of Science database are examined, it is seen that the main topic of 471 publications is "Nature-Based Solutions", 54,410% in the "Environmental Sciences" area, 18.896% in the "Environmental Studies" area, and 13,376% in the "Ecology" area (Table 1.3).

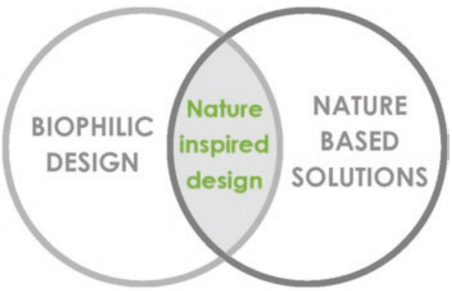


Fig. 1.1 The intersection of biophilic design and nature-based solution

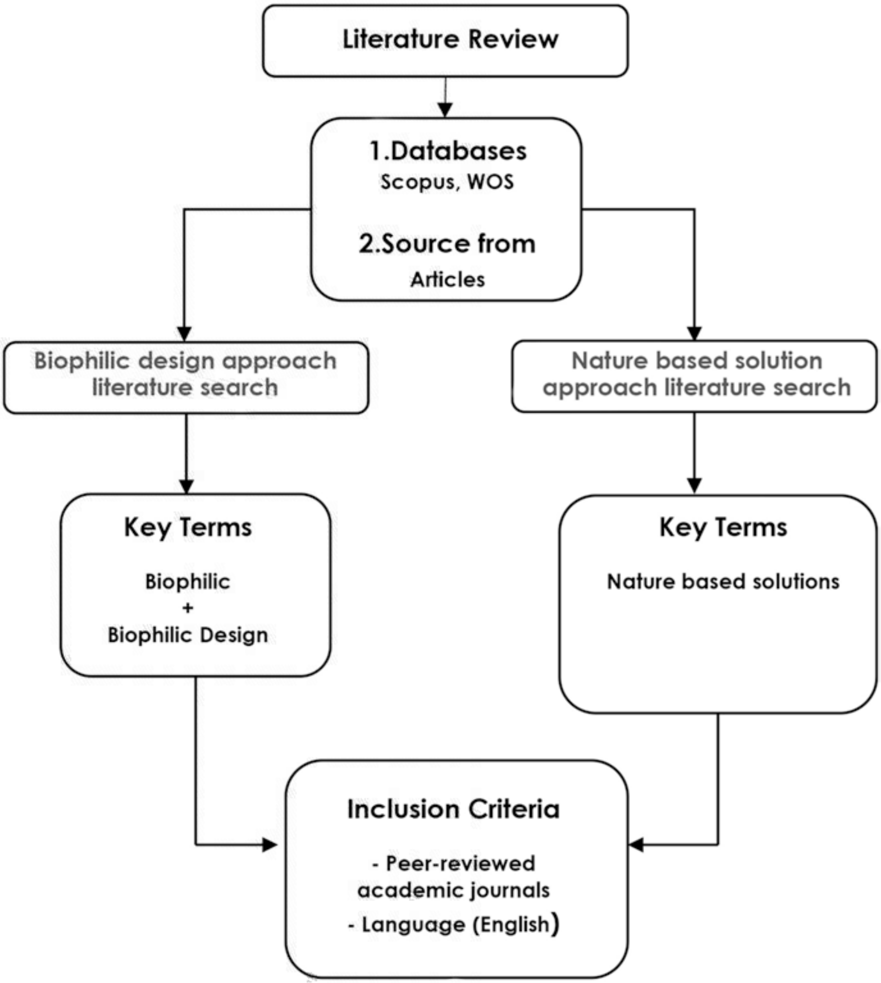


Fig. 1.2 Database diagram

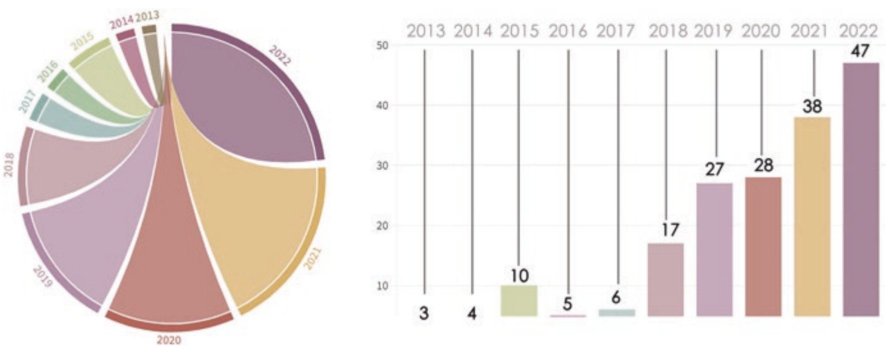


Fig. 1.3 Web of Science biophilic design publication rate in 2013–2022

Table 1.2 Record count in 2013–2022

Publication years	Record count	% of 194
2022	47	24.227%
2021	38	19.588%
2020	28	14.433%
2019	27	13.918%
2018	17	8.763%
2015	10	5.155%
2017	6	3.093%
2016	5	2.577%
2014	4	2.062%
2013	3	1.546%

Table 1.3 Percentage distribution by Web of Science categories

Web of Science categories	Record count	% of 471
Environmental sciences	255	54.140%
Environmental studies	89	18.896%
Ecology	63	13.376%
Green sustainable science technology	61	12.951%
Engineering environmental	54	11.465%
Water resources	52	11.040%
Forestry	33	7.006%
Urban studies	33	7.006%
Plant sciences	23	4.883%
Multidisciplinary sciences	20	4.246%
Geosciences multidisciplinary	19	4.034%

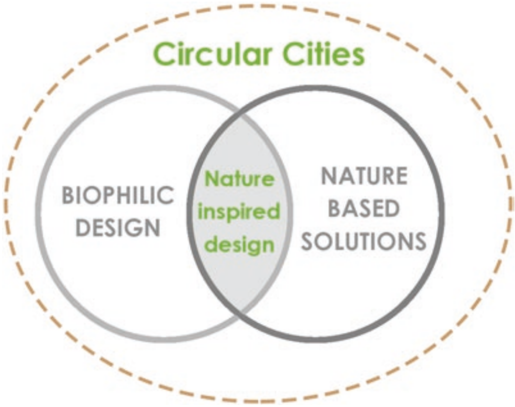
1.4 Biophilic Design and Nature-Based Solutions in Circular Cities

If cities could become adaptable urban ecosystems with biophilic design and NbS approaches, their ecological footprint would be reduced. At the same time, urban resource security will increase, the health of the urban population will improve, urban welfare will increase, and urban greenhouse gas emissions will decrease. These are the main goals that support the circular city.

These goals are actually the common points of biophilic design and NbS (Fig. 1.4). Therefore, biophilic design and NbS can help address these issues as a circular development approach to the regeneration of our cities. However, although biophilic design and nature-based solutions are concepts that are so close to each other, no study in which these two concepts are combined has been found among the sources reached.

Nature-based approaches, together with biophilic elements and attributes (Kellert 2018), can be combined in many parts of the city. These can be considered in three scales. In a large scale, “green corridors, coastal areas, and urban forests” appear as “urban parks, pocket parks” in a medium scale, and applications in small scales are indoor and outdoor applications (Fig. 1.5).

Fig. 1.4 The relationship between circular cities, biophilic design, and nature-based solutions



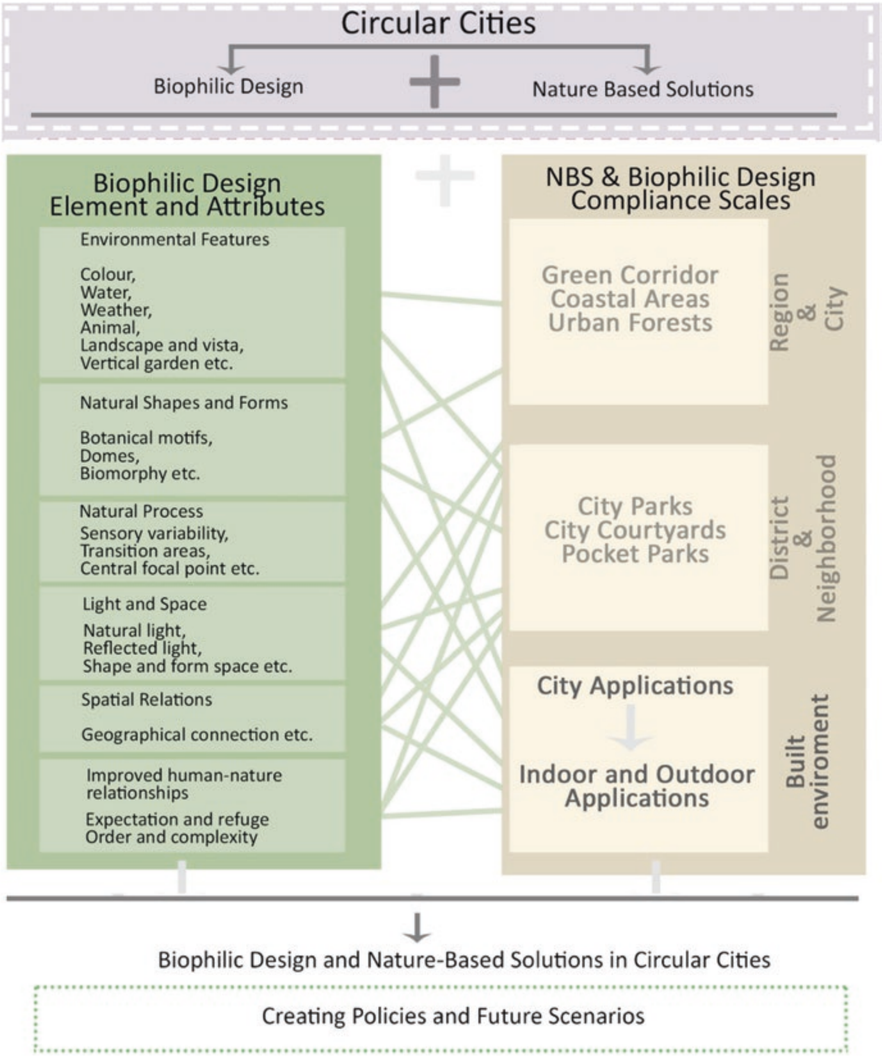


Fig. 1.5 Circular city policies and future scenario diagram

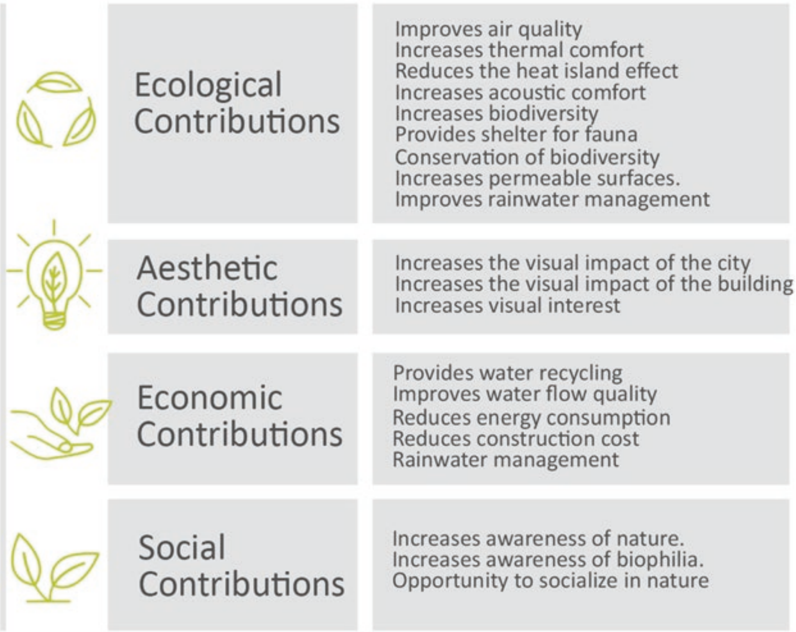


Fig. 1.6 Contribution of nature-based approaches to cities

When city applications are implemented as shown in Fig. 1.6, they can be categorized into four main groups, i.e., ecological, aesthetic, economic, and social contributions.

1.5 Conclusion

Rapid and unplanned urbanization and uncontrolled population growth brought about by metropolitanization create negative environmental effects. For this reason, studies investigating alternative solutions for nature-based approaches are on the agenda of countries. As these problems progress, loss of biodiversity and ecosystem services and urban resilience problems are expected to increase.

In this process, cities and societies that try to adapt by keeping up with the flow instead of resisting change will suffer minimal damage from the climate crisis. This process can be evaluated as an opportunity to develop while preserving nature. The restrictions of the Covid-19 global epidemic have shown that nature enters the recovery process at a great speed when the pressure on nature is reduced. Cities can also heal together with nature. The most important example of this will be with the cooperation of biophilic design and NbS, which produces solutions inspired by nature.

Urban systems are dependent on nature and natural resources. Where possible, nature-based planning of investments in cities will make cities resilient. In order to achieve the sustainable development goals, nature-based solutions must be implemented.

As a result, the research is at the common intersection of the concept of circular cities, NbS, and biophilic design. This study aims to both contribute to the literature on circular cities with these concepts and simultaneously establish foundational data for future research. Findings on these concepts show that these approaches can solve many ecological, social, and economic problems facing cities. This triple intersection also defines the potential benefits of adopting circular urban systems. Therefore, taking a circular approach to development can help revitalize our cities.

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Chapter 2
The Role of Multipurpose NbS Interventions in Increasing the Circularity of Cities

Behrouz Pirouz, Michele Turco, Stefania Anna Palermo, Anna Chiara Brusco, Behzad Pirouz, Hana Javadi Nejad, and Patrizia Piro

Abstract Climate change affects all nations and requires increasing awareness about sustainability and circularity. A vast percentage of the population lives in urban areas, about 75% in Europe. There are plenty of aspects in cities toward sustainability, including environmental, social, human, economic, and ecological. In addition, there are numerous kinds of nature-based solutions (NbS), such as green infrastructures, natural treatment and recovery, rainwater management, and increases in green spaces. However, using several NbS, such as green roofs, renewable energy, or urban farming in one building is not possible simply due to the limit of the roof area. Therefore, to consider as many aspects as possible simultaneously, one way could be multidisciplinary NbS interventions. In this regard, this study aims to analyze multipurpose NbS interventions to maximize sustainable systems and increase the circularity of cities. Therefore, the possibility of mixing green roofs and solar panels, urban farming using gray water and atmosphere water harvesting, multipurpose plants for green spaces for landscape and animal food and biofuel, and similar techniques and innovative methods have been investigated. Moreover, the advantages of the selected multipurpose NbS interventions are presented. The outcomes show the role of the purpose techniques in increasing the efficiency, sustainability, acceptance rate by customers, and circularity level of the city.

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A. Stefanakis et al. (eds.), *Nature-based Solutions for Circular Management of Urban Water*, Circular Economy and Sustainability,
https://doi.org/10.1007/978-3-031-50725-0_2

Keywords Domestic water management · Flood management · Urban farming · Biofuel · Energy · Circular city

2.1 Introduction

2.1.1 Urbanization and Climate Change

Around half of the world's population lives in urban areas, and the urbanization trend is increasing. According to predictions, the urbanization rate will reach more than 80% by 2050 (UNEP 2012). One of the consequences of this variation would be global climate change (Bona et al. 2023). Increasing urbanization and natural hazard risks by climate change raise humans' vulnerability, which settled more concentrated in the cities (Brinkley et al. 2013). In addition, the features of the cities, such as less permeable areas, amplified the intensity of climate change impacts (Hobbie and Grimm 2020). The urbanization rate depends on population growth, which is increasing unstoppably in many areas. Therefore, understanding how urbanization changes the environment and how the impacts (land use, temperature, infiltration rate, wind velocity, rainfall, heat island, evaporation, evapotranspiration, energy balance, etc.) can be minimized would be useful to increase the livability of cities (Maheshwari et al. 2020).

2.1.2 Nature-Based Solutions (NbS) and Their Advantages in the Urban Environment

The European Commission (EC) has defined NbS as follows (Maes and Jacobs 2017):

> …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 simultaneously provide economic, social, and environmental benefits.

The main identified principal advantages of NbS by the EC (European Commission 2015):

- NbS could increase sustainable urbanization, increase economic growth besides improving the environment, enhancing human well-being, and making cities more attractive.
- NbS could restore degraded ecosystems and thus improve the resilience of ecosystems.
- NbS could mitigate climate change.
- NbS could enhance the storage of carbon.
- NbS could improve natural risk management and decrease natural disaster damages.

There is a growing recognition that NbS, as an integrated approach, is a vital strategy for climate change (Seddon et al. 2020, 2021). NbS are interventions where people try to restore nature and improve urbanization as a part of nature that brings benefits for people and biodiversity (Cohen-Shacham et al. 2019) while at the same time supporting sustainable development goals (SDGs) (Gómez Martín et al. 2020; Maes et al. 2019).

NbS interventions have the potential to deal with climate adaptation and mitigation (Langergraber et al. 2021), decrease flood risk (Brunetti et al. 2018; Carbone et al. 2015), increase food and water security (Boelee et al. 2017), mitigation of climate change, improvement of sustainable livelihoods, ecosystems, and biodiversity (Cohen-Shacham et al. 2019), improvement of building thermal behavior (Maiolo et al. 2020), a decrease in energy consumption (Pirouz et al. 2020b), and so forth. In addition, NbS could address one or more urban challenges in sustainable ways (Pirouz et al. 2020a), such as the environment, economy, society, and health benefits (Raymond et al. 2017). The major advantages of NbS are as follows (Liquete et al. 2016; Raymond et al. 2017):

- Social health and benefits: Reduce flood risk and improve people's recreation and health.
- Environmental benefits: Improve water quality and support wildlife.
- Economic benefits: Produce market goods and reduce public costs.

However, there are some drawbacks to some NbS. The main difficulties of some NbS, like green building, are as follows (Banerjee and Akuli 2014):

- High implementing costs.
- Lack of information about the advantages.
- Lack of human resources and skills.
- Uncertainty about performances.
- Difficulties in finding alternative raw material inputs and manufacturing technology.

2.1.3 Sustainable Development and NbS

The impacts of human activities (industrialization, burning fossil fuels, urbanization, carbon emissions, population growth, etc.) alter the climate and negatively affect the environment, and sustainable development means the procedures for sustaining human activities in the present and future (Lavrinenko et al. 2019). In 1992, this became one of the most urgent focuses for international policy at the United Nations Earth Summit (Chichilnisky 1997). A low-carbon city is a city with minimum carbon emissions. In contrast, a low-carbon policy plays a role in sustainability but does not guarantee it. In fact, a sustainable city means a city with long-term socioeconomic sustainability, minimum resource abuse, and without negative ecological impacts (UNEP 2012).

The 17 sustainable development goals (SDGs) include SDG 1: No Poverty, SDG 2: Zero Hunger, SDG 3: Good Health and Well-being, SDG 4: Quality Education, SDG 5: Gender Equality, SDG 6: Clean Water and Sanitation, SDG 7: Affordable and Clean Energy, SDG 8: Decent Work and Economic Growth, SDG 9: Industry, Innovation, and Infrastructure, SDG 10: Reduced Inequality, SDG 11: Sustainable Cities and Communities, SDG 12: Responsible Consumption and Production, SDG 13: Climate Action, SDG 14: Life Below Water, SDG 15: Life on Land, SDG 16: Peace and Justice Strong Institutions, SDG 17: Partnerships to achieve the Goal (United Nations Foundation 2023).

2.1.4 Circularity of Cities and NbS

A circular city means moving from a linear economy to a circular economy (CE). CE system means minimizing resource consumption, waste, and emissions (Langergraber et al. 2020; Pearlmutter et al. 2020), decreasing the cities' environmental footprint, closing the loops of urban material and resource flows, and creating new business opportunities (Bjørn Vidar Vangelsten et al. 2020).

The key parameters in circularity are as follows (Cruz 2019; OECD 2020; Oral et al. 2021; Williams 2021):

– Society and environment (improvements of cities' ecological footprint, public health, urban safety, air, forest, land use, built environment and limiting harmful urban effects).
– Supply chain (consumption of natural resources, circularity of resources and materials, domestic product production, repair, waste, reuse, water, etc.)
– Partnership among stakeholders.
– Energy.
– Economic and business (agriculture, food, tourism, improve existing urban conditions).
– Infrastructure and technology (mobility and industry).
– Financial, correlated to cost or cost-saving related to the circular economy.
– Market circularity.
– Governments (public administration, suitable strategies, resistance to adopt policies).

There are interconnections between NbS and circular economy and circular city. For example, taking advantage of buildings' roofs (green buildings) that include green roofs, living walls, green facades, house trees, etc. can increase the circularity of the cities (Calheiros and Stefanakis 2021). These types of NbS can improve ecosystem services, thus contributing to a circular economy (CE) in several ways (Alhashimi 2018; Allen et al. 2015; Pearlmutter et al. 2020):

– Green building materials (materials more natural, more economical with less waste, water usage, energy usage, etc.).
– Green building systems (minimizing impacts on the environment, improving urban life quality, etc.).

– Green building sites (minimizing environmental conflicts by the buildings).
– Improve and protect biodiversity;
– Improve and protect ecosystems.

2.1.5 Urban Farming as a Multidisciplinary NbS

Urban farming could play a key role in a circular city (CC) as it can maximize the reuse of resources for food and biomass production and minimize external resources (Canet-Martí et al. 2021). The shorter distance between consumers and food production sites through urban farming could decrease costs from delivery to storage, fuel costs, and impact on clean air and climate change mitigation. Moreover, short food supply chains contribute directly to food security by reducing reaction times to consumer demands (Aubry and Kebir 2013; Pölling and Mergenthaler 2017; Song et al. 2021). Moreover, urban gray water can be reused for not-drinking usage such as urban farming, thus decreasing purified water resource consumption (López Zavala et al. 2016; Ren et al. 2020; Sahoo and Manna 2018). Treatment and reuse of gray water could save 29–47% of drinking water consumed (Humeau et al. 2011).

Advantages of urban food production (Liquete et al. 2016; Massonneau 2012; Skar et al. 2020; van Niekerk et al. 2011):

– Production of fresh vegetables, fruits, flowers, etc.
– Production of small animals on rooftops.
– Reduction of urban runoff.
– Thermal advantages for the building.
– Reduction of urban heat island effect.
– Social, environmental, and economic advantages.
– Reduction greenhouse gas emissions.
– Climate change adaptation.
– Disaster risk management.
– Sustainable cities.
– Water resource management.
– Improvement of biodiversity.

Disadvantages of urban food production (De Zeeuw et al. 2011; Draper 2010; Smit et al. 1997; van Niekerk et al. 2011):

– Exposure to pesticides.
– Potential for disease transmission (i.e., bird/chicken flu in the case of animal production).
– Contamination.
– The unsuitability of urban soil/air for food production.
– High weight.
– Costs of protection and structural supports.
– Maintenance cost.

The literature review analysis shows the advantages of NbS in the circularity and sustainability of cities. However, a rank system to consider both circularity and sustainability parameters is missed in the previous studies and, therefore, will be analyzed in this research. Moreover, the role of new NbS with more multifunctionality is missed in the previous studies and will be considered in the current research.

2.2 Materials and Methods

This study tried to improve the circularity and sustainability rate of the NbS and analyze the role of multipurpose NbS interventions to achieve a better result. The study flowchart is shown in Fig. 2.1.

As shown in Fig. 2.1, in the first step, to be able to analyze and compare the advantages of multifunctional NbS, we selected the NbS based on the results of a study by Oral et al. (2021), and we applied the calculated total circularity score (TCS). In the second step, we did another analysis and calculated the total sustainability score (TSS), and we created another qualitative assessment score as the total score (TS) by mixing both scores, meaning circularity and sustainability. In the third step, we changed the elements of the NbS in a way to make the conventional NbS more multipurpose, and repeated the previous steps. In the fourth step, we compared the new multipurpose NbS scores to the previous ones and, finally, some recommendations for improving the applications of NbSs.

2.2.1 Selected NbS

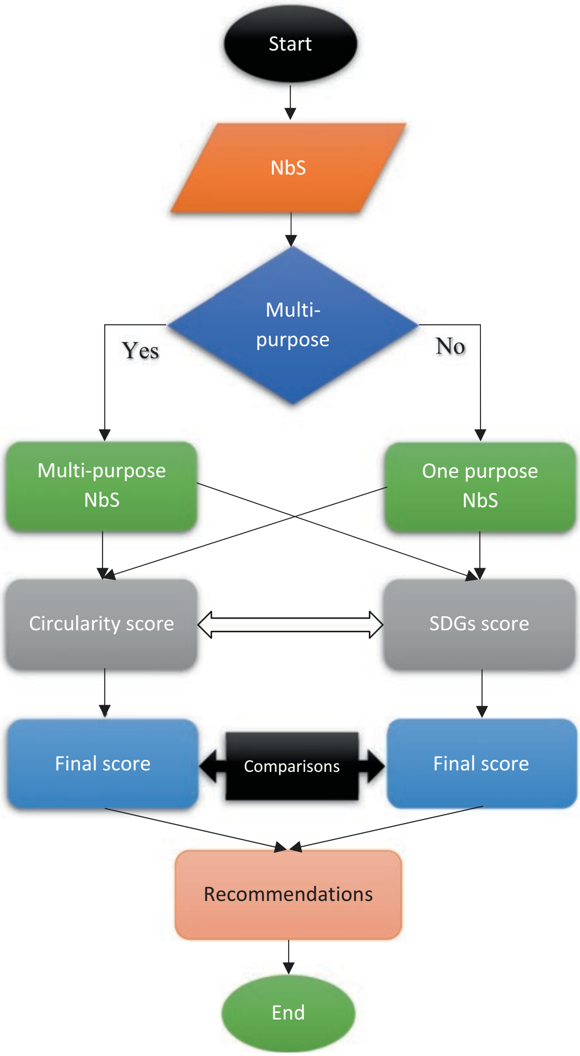
The selected NbS are presented in Table 2.1.

2.2.2 Fuzzy Scale

Fuzzy Number Fuzzy numbers are widely used in the representation of uncertainty in applied sciences. Suppose that R is the set of all real numbers (Saeidifar 2011). The fuzzy number $\tilde{A}$ expressed with the following membership function for all $x \in R$:

$$\mu_{\tilde{A}}(x) = \begin{cases} A_{\mathrm{L}}(x), & a \le x \le b \\ 1, & b \le x \le c \\ A_{\mathrm{R}}(x), & c \le x \le d \\ 0, & \text{otherwise} \end{cases}$$

Fig. 2.1 A flowchart of the study



where a, b, c, and d are real numbers such that $a < b \leq c < d$, $A_L(x)$ is a real-valued function that is increasing and right continuous, and $A_R(x)$ is a real-valued function that is decreasing and left continuous.

Triangular Fuzzy Number Triangular fuzzy number (TFN) is one of the most widespread and common fuzzy data representations in applied sciences (Borovička 2014). The TFN $\tilde{A}$ is denoted by $\tilde{A} = (\alpha, \beta, \gamma)$, while the following function is interpreted as the membership function of this fuzzy number:

Table 2.1 Selected NbS for circularity and NbS analysis

No.	Selected NbS units	Category	Total circularity score (Oral et al. 2021)
1	Infiltration trench	Units for rainwater management	7
2	Bioretention cell (rain garden)		16
3	Dry swale		6
4	Riparian buffer		19
5	Extensive green roof	Vertical green infrastructure & green roofs	6
6	Intensive green roof		15
7	Treatment wetland	Remediation, treatment, & recovery	21
8	Anaerobic treatment		3
9	River restoration	River restoration	24
10	Coastal erosion control		2
11	Large urban park	Greening intervention (i.e., public green space)	14
12	Productive garden	NbS units for food and biomass production	12

$$\mu_{\tilde{A}}(x) = \begin{cases} 0 & x < \alpha \\ \dfrac{x-\alpha}{\beta-\alpha}, & \alpha \le x \le \beta \\ \dfrac{\gamma-x}{\gamma-\beta}, & \beta \le x \le \gamma \\ 0 & x > \gamma \end{cases}$$

In Fig. 2.2, the geometric representation of a triangular fuzzy number is shown.

α-Cut Operation (Cheng 2004) If a triangular fuzzy number $\tilde{A} = (a,b,c)$ and any real number $\alpha \in [0, 1]$ are given, then the α-cut or α-level of $\tilde{A}$ denoted by A_α is defined as the following interval:

$$A_\alpha = [(b-a)\alpha + a, -(c-b)\alpha + c]$$

Operation of Triangular Fuzzy Number (Cheng 2004; Zeng et al. 2017) Let $\tilde{A} = (\alpha_1, \beta_1, \gamma_1)$ and $\tilde{B} = (\alpha_2, \beta_2, \gamma_2)$ be two fuzzy triangular numbers. In this case, the addition, subtraction, and multiplication operators for these two fuzzy numbers are, respectively, expressed as follows:

I. Addition operator (Cheng 2004):

$$\tilde{A} + \tilde{B} = (\alpha_1, \beta_1, \gamma_1) + (\alpha_2, \beta_2, \gamma_2) = (\alpha_1 + \alpha_2, \beta_1 + \beta_2, \gamma_1 + \gamma_2)$$

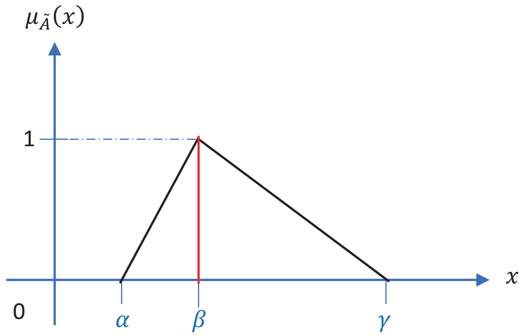


Fig. 2.2 Representation of a triangular fuzzy number (TFN). (Cheng 2004)

II. Subtraction (Cheng 2004):

$$\tilde{A} - \tilde{B} = (\alpha_1, \beta_1, \gamma_1) - (\alpha_2, \beta_2, \gamma_2) = (\alpha_1 - \gamma_2, \beta_1 - \beta_2, \gamma_1 - \alpha_2)$$

III. Multiplication (Zeng et al. 2017):

$$\tilde{A} \times \tilde{B} = (\alpha_1, \beta_1, \gamma_1) \times (\alpha_2, \beta_2, \gamma_2) = (\alpha_1 \alpha_2, |\alpha_1| \beta_2 + |\alpha_2| \beta_1, |\alpha_1| \gamma_2 + |\alpha_2| \gamma_1)$$

Priority Weights with Triangular Fuzzy Numbers Scale

Various scales have been presented in the case of fuzzy triangular numbers for weighting the degree of importance of parameters. In this chapter, we have used the triangular fuzzy importance scale presented in (Elevli 2014). See Table 2.2 for details.

Figure 2.3 shows the intersection between these fuzzy linguistic scales (TFN scales).

Algorithm for Fuzzy Weighting Assignment and Calculation of TS of Each NbS (Table 2.3)

Step 1. Construct the fuzzy matrix, FM (according to the triangular fuzzy importance scale in Table 2.2), of $m \times 17$, where m represents the number of NbS and n represents the number of SDGs:

$$\mathrm{FM} = \begin{pmatrix} \mathrm{FS}_{11} = (\alpha_{1,1}, \beta_{1,1}, \gamma_{1,1}) & \cdots & \mathrm{FS}_{1n} = (\alpha_{1,17}, \beta_{1,17}, \gamma_{1,17}) \\ \vdots & \vdots & \vdots \\ \mathrm{FS}_{m1} = (\alpha_{m,1}, \beta_{m,1}, \gamma_{m,1}) & \cdots & \mathrm{FS}_{mn} = (\alpha_{m,17}, \beta_{m,17}, \gamma_{m,17}) \end{pmatrix} \quad (2.1)$$

where $\mathrm{FS}_{i,j} = (\alpha_{i,j}, \beta_{i,j}, \gamma_{i,j})$ for $i = 1, \ldots, m, j = 1, \ldots, 17$ are the fuzzy value delivered by NbS_i for SDG_j.

Step 2. Compute the normalized fuzzy matrix (NFM) using cumulative normal distribution function using Eq. (2.3) to scale all values of the matrix in the range of $(0, 0, 0)$ and $(1, 1, 1)$:

Table 2.2 Triangular fuzzy importance scale (Elevli 2014)

Linguistic scale	TFN scale
Very weak (VW)	(0, 0, 1.5)
Weak (W)	(0, 1.5, 3)
Medium weak (MW)	(1.5, 3, 5)
Medium (M)	(3, 5, 6.5)
Medium-high (MH)	(5, 6.5, 8)
High (H)	(6.5, 8, 10)
Very high (VH)	(8, 10, 10)

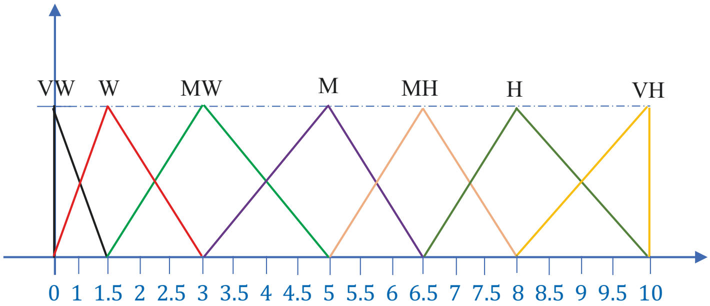


Fig. 2.3 The intersection between fuzzy linguistic scales

Table 2.3 Fuzzy weighting algorithm for calculation of TS

NbS	NbS score	SDG						TSS	TS
		SDG_1	SDG_2	⋯	SDG_j	⋯	SDG_{17}		
NbS_1	TCS_1	$FS_{1,1}$	$FS_{1,2}$	⋯	$FS_{1,j}$	⋯	$FS_{1,17}$	TSS_1	TS_1
NbS_2	TCS_2	$FS_{2,1}$	$FS_{2,2}$	⋯	$FS_{2,j}$	⋯	$FS_{2,17}$	TSS_2	TS_2
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
NbS_i	TCS_i	$FS_{i,1}$	$FS_{i,2}$	⋯	$FS_{i,j}$	⋯	$FS_{i,17}$	TSS_i	TS_i
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
NbS_m	TCS_m	$FS_{m,1}$	$FS_{m,2}$	⋯	$FS_{m,j}$	⋯	$FS_{m,17}$	TSS_m	TS_m

$$\mathrm{NFM} = \begin{pmatrix} \mathrm{NFS}_{11} = \left(\varnothing\left(\alpha_{1,1}\right), \varnothing\left(\beta_{1,1}\right), \varnothing\left(\gamma_{1,1}\right)\right) & \cdots & \mathrm{NFS}_{1n} = \left(\varnothing\left(\alpha_{1,17}\right), \varnothing\left(\beta_{1,n}\right), \varnothing\left(\gamma_{1,17}\right)\right) \\ \vdots & \vdots & \vdots \\ \mathrm{NFS}_{m1} = \left(\varnothing\left(\alpha_{m,1}\right), \varnothing\left(\beta_{m,1}\right), \varnothing\left(\gamma_{m,1}\right)\right) & \cdots & \mathrm{NFS}_{mn} = \left(\varnothing\left(\alpha_{m,17}\right), \varnothing\left(\beta_{m,17}\right), \varnothing\left(\gamma_{m,17}\right)\right) \end{pmatrix} \tag{2.2}$$

where NFS_{ij} represents cumulative normal distribution function with mean μ and variance σ, which is computed using Eq. (2.3):

$$\mathrm{NFS}_{ij} = \left(\int_{-\infty}^{\alpha_{i,j}} e^{-(x-\mu)^2/2\sigma^2}\,dx, \int_{-\infty}^{\beta_{ij}} e^{-(x-\mu)^2/2\sigma^2}\,dx, \int_{-\infty}^{\gamma_{i,j}} e^{-(x-\mu)^2/2\sigma^2}\,dx\right) \tag{2.3}$$

Step 3. Calculate the index TSS_i using Eq. (2.4):

$$TSS_i = \sum_{17}^{j=1} NFS_{ij} = \sum_{17}^{j=1} \left(\varnothing\left(\alpha_{i,j}\right), \varnothing\left(\beta_{i,j}\right), \varnothing\left(\gamma_{i,j}\right) \right) \tag{2.4}$$

Step 4. Calculate the rank of NbS based on descending order of TS_i (using Eq. (2.5)), i.e., the NbS having maximum TS_i value will be ranked first, whereas the NbS with minimum value will be ranked last.

$$TS_i = TCS_i * TSS_i \tag{2.5}$$

2.3 Results and Discussion

2.3.1 Contributions of the NbS Units to SDGs

Figures 2.4, 2.5, 2.6, 2.7, 2.8 and 2.9 present the contributions of the main NbS units to different SDGs. The contributions have been determined according to the dependency of each unit on the SDGs, for example, in Fig. 2.4, units for rainwater management. The unit's contribution is high in SDG 3: Good Health and Well-being and SDG 6: Clean Water and Sanitation, and low in SDG 9: Industry, Innovation and Infrastructure, SDG 11: Sustainable Cities and Communities, and SDG 13: Climate Action. The contributions to other SDGs are not too much and therefore are neglected in the figures.

Fig. 2.4 Units for rainwater management contribution to SDGs