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The role of green roofs in urban Water-Energy-Food-Ecosystem nexus: A review

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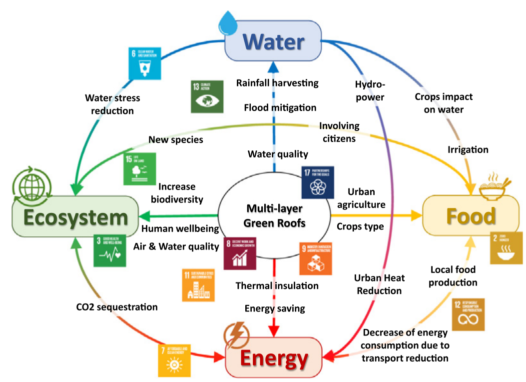
HIGHLIGHTS

- The WEFE nexus approach is used to investigate the potential benefits of green roofs
- Green roofs contribute to achieving Development Goals of the 2030 Sustainable Agenda
- Multilayer green roofs are beneficial for the creation of smart and resilient cities

GRAPHICAL ABSTRACT



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ABSTRACT

Green roofs are strategic tools that can play a significant role in the creation of sustainable and resilient cities. They have been largely investigated thanks to their high retention capacity, which can be a valid support to mitigate the pluvial flood risk and to increase the building thermal insulation, ensuring energy saving. Moreover, green roofs contribute to restoring vegetation in the urban environment, increasing the biodiversity and adding aesthetic value to the city. The new generation of multilayer green roofs present an additional layer with respect to traditional ones, which allows rainwater to be stored, which, if properly treated, can be reused for different purposes. This paper offers a review of benefits and limitations of green roofs, with a focus on multilayer ones, within a Water-Energy-Food-Ecosystem nexus context. This approach enables the potential impact of green roofs on the different sectors to be highlighted, investigating also the interactions and interconnections among the fields. Moreover, the Water-Energy-Food-Ecosystem nexus approach highlights how the installation of traditional and multilayer green roofs in urban areas contributes to the Development Goals defined by the 2030 Sustainable Agenda.

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1. Introduction

Population growth and the increase of urbanization have characterized the last decades and are projected to continue with this trend in the future, with 2/3 of humans living in cities by 2050 (UN, 2018). These phenomena are altering the natural balance and modifying the interactions between water, energy, food and the ecosystem. Recent studies investigated and discussed in depth the water, energy and food systems, highlighting the importance of evaluating these components not only with a silo approach, but also as an integrated water-energy-food (WEF) nexus (D'Odorico et al., 2018; Hoff, 2011; Leck et al., 2015). Indeed, these systems are co-dependent and they can only be fully understood if analysed with an integrated approach (Bazilian et al., 2011; Bizikova et al., 2013; Chang et al., 2020).

This innovative approach plays a significant role in urban areas (Newell et al., 2019), where the intense urbanization has increased the demand for water, energy and food and has had a negative impact on the environment. In order to create resilient and sustainable cities, guaranteeing economic development, social equity and ecosystem protection, a high level of interactions among the WEF sectors is required. In particular, planning, policies, regulations and coordination programmes across these sectors are essential to increase the efficiency of the urban systems (Hoff, 2011; Sperling and Berke, 2017).

Urban WEF nexus theories and models available in literature mainly focus on the integration, at different spatial and temporal scales, of urban agricultural methods, water treatment technologies and innovative energy solutions, often in relation to other aspects, such as environment or society (Covarrubias, 2019). Some recent WEF studies have also included the linkages to the environment and the ecosystem in the urban nexus analysis (Beck and Villarroel, 2013; Hellegers et al., 2008; Martinez-Hernandez et al., 2017; Oswald, 2016; Schmidt and Matthews, 2018; Staupe-Delgado, 2019), highlighting how these factors cannot be neglected in a comprehensive investigation. Although there is not a unique and standardized approach to investigate the WEF urban nexus and ecosystem and environment, there is the need to evaluate these different sectors together, analysing their interactions and connections.

In this work, we will focus on the water-energy-food-ecosystem (WEFE) security nexus approach to contribute to a sustainable and resilient development of cities. This method can be applied to study benefits and limitations of a selected tool, technology or strategy, since it evaluates their impacts on all the potential sectors. Moreover, this approach aims to identify not only the implications in each sector, but also to analyse the interconnections and feedbacks within the WEFE system. In this context, it is possible to understand fully the impact and implications of a new tool or technology on the sustainable development.

Compared to traditional technologies, green innovations present a higher complexity and novelty, requiring a larger collaboration with external actors and among the internal ones (Ardito et al., 2016; Ardito et al., 2019; Messeni Petruzzelli et al., 2011). These findings were supported by Messeni Petruzzelli et al. (2011), who investigated the citations of green and non-green traditional technology patents in the 5 years after the publications and showed the differences between these two types of innovation. Green technologies have shown to have a positive influence on the technological development of the industry: green solutions, including the ones derived from the public research, can strengthen the industries, which deal with environmental technologies (Ardito et al., 2016; Ardito et al., 2019). A WEFE nexus analysis can further improve the understanding of the potential impacts of green solutions, highlighting their benefits for a sustainable and smart development, especially in urban areas.

Among the several nature-based solutions proposed in literature to mitigate the urbanization effects and ensure a sustainable urban development, green roofs, and in particular multilayer green roofs, can largely benefit from the WEFE nexus analysis. Green roofs are, in fact, generally investigated with a special focus on one single sector: most of the studies investigate the impact of green roofs on water, analysing the pluvial flood mitigation capacity, and on energy, evaluating the potential energy saving for the building. Green roofs, however, present numerous benefits, involving multiple sectors and highlighting strong interconnections among them, and the potential of this tool can be fully understood with an integrated WEFE approach.

Multilayer green roofs, also called blue-green roofs, are innovative instruments that combine green roof technology with a rainwater harvesting system (Shafique et al., 2016a). As showed in Fig. 1, multilayer green roofs present all the characteristic elements of a green roof: vegetation coverage, soil layer, geotextile filtering membrane, drainage layer and protective waterproof membrane to protect the building. Compared to traditional green roofs, multilayer green roofs present a water tank as an additional layer, which enables rainwater that percolates from the soil layer to be harvested and stored. Collected water can be later used for several purposes, such as irrigation of the green roof itself. A gate can be installed to regulate the water level in the tank. Different variations of this tool are commercially available, which enable the water level to be controlled manually or remotely with the help of different sensors.

Green roofs can be classified depending on the soil layer thickness. The extensive structures are characterized by a soil depth < 15–20 cm, instead solutions with a thicker layer are called intensive. Extensive green roofs are usually preferred, since they are generally less expensive, easier to install and they present a lighter soil substrate (Skjeldrum and Kvande, 2017). The soil thickness limits the root length and consequently, the vegetation type that can be installed. Compared to traditional green roofs, multilayer ones can recreate the habitat for a wider range of vegetation, thanks to the water that is stored in the tank and that can be easily used for irrigation.

Multilayer green roofs present benefits in different fields (i. e. storm water retention, water quality enhancement, energy saving, food

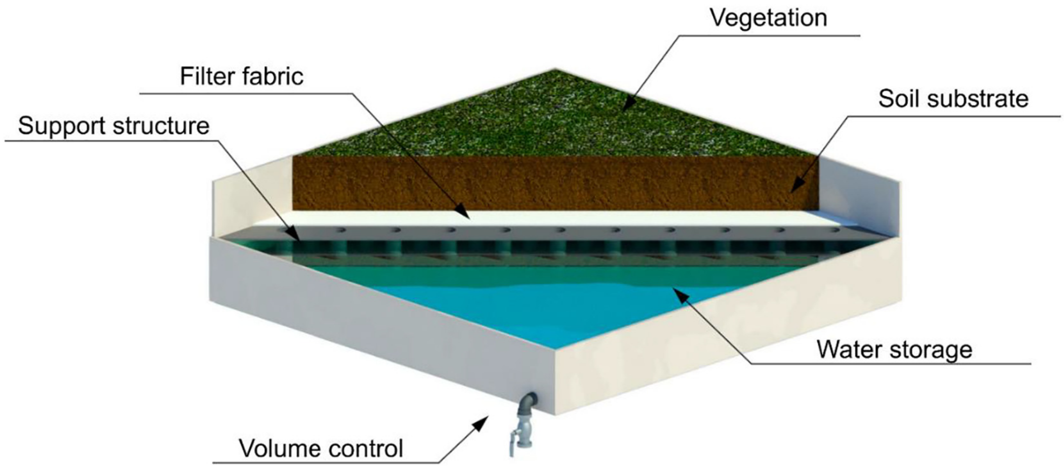


Fig. 1. Schematic representation of a multilayer green roof. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

production) and their performance has been investigated in several areas with different climatological conditions, showing a high flexibility (Andenæs et al., 2018; Muhammad and Reeho, 2017; Shafique et al., 2016a; Shafique et al., 2016b). This tool can, hence, be a valid support to represent the application of the WEFE nexus approach in an urban context (Baek and Han, 2015; Shafique et al., 2018) since it has implications in different sectors and most of them are interconnected. In this framework, the WEFE nexus approach can help understand and highlight the role of the green roofs, and in particular multilayer ones, in the development of sustainable cities.

This study presents a review of benefits and limitations of the installation of multilayer green roofs in urban areas, following a WEFE nexus approach, which analyse not only the potential in each single field, but discuss the implications in a more complete context. Fig. 2 summarizes the analyses that will be discussed in this paper: the multilayer green roofs are beneficial for water (reducing pluvial flood, harvesting rainwater and improving the water quality), for energy (creating a thermal insulation for buildings), for food (through the urban agriculture) and for the ecosystem (increasing biodiversity and adding aesthetic value to the city), and they also provide additional advantages thanks to the

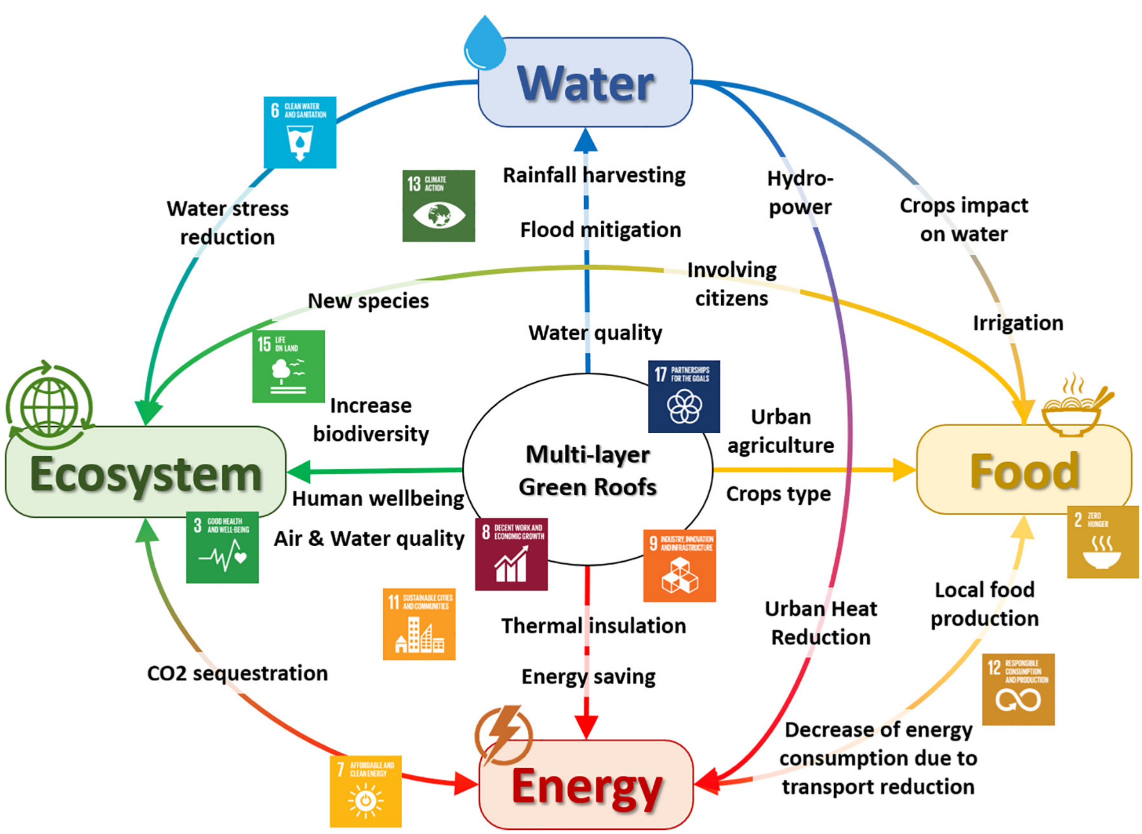


Fig. 2. Contributions of multi-layer green roofs to the WEFE nexus, in relation to benefits and contribution to the SDGs. Arrows indicate the direction of the benefit: for example, the blue-yellow line that connects water in the direction of food suggests that collected water can be used for irrigation, supporting the food production. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

interaction among the different sectors. For example, the harvested water can be used for irrigation to facilitate the food production: this highlights the strong water-food nexus. Arrow direction indicates the field towards where the benefit is oriented. Potential contributions of multilayer green roof installation to the Sustainable Development Goals (SDGs) defined in the 2030 Agenda for Sustainable Development (GA, 2015), are also plotted in Fig. 2.

The most important findings and results available in literature are summarized in Table 1. This table can be read as a symmetrical matrix, which shows the main contributions of multilayer green roofs, analysed for the different fields (water, energy, food and ecosystem). The silo approach is represented on the diagonal of the table (highlighted with different colours for the different fields), while the integrated nexus approach is described through an iconic representation in the upper part of the matrix and through a summary of relevant references and key-points in the lower part. The green roof potential benefits for each field or for the combination of 2 different fields summarized in Table 1 correspond to the ones highlighted in Fig. 2.

The paper is structured as follows. Potential benefits of multilayer green roofs will be analysed at first (Section 2) following a so-called "silo approach", i. e. focusing only on one single sector (Water, Energy, Food and Environment). In Section 3, instead, the multilayer green roof is analysed investigating the interconnection between sectors, following an integrated WEFE nexus approach. A conclusive discussion is presented in Section 4, where the potential of multilayer green roofs is highlighted in relation to the contribution to the SDGs.

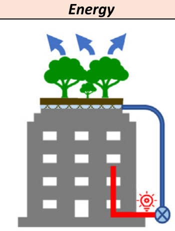
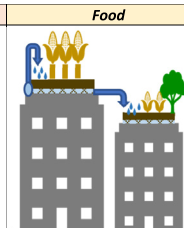
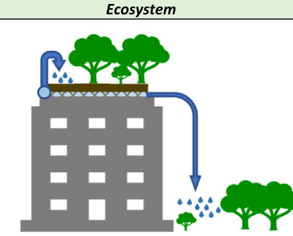
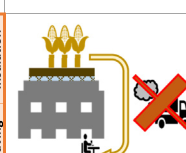
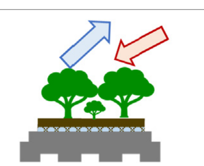
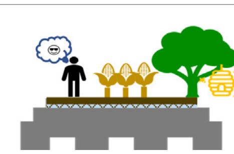
2. Silo approach

In this section, the multilayer green roof is explored following a silo approach, where the potential benefits and limitations are investigated only in relation to a single sector. According to this traditional approach, the potential impacts on Water, Energy, Food and Environment are evaluated separately, while interactions and feedback among these sectors are discussed in the next section with a nexus analysis. The main findings of following a silos approach to analyse the potential benefits of green roofs are summarized along the diagonal of Table 1.

2.1. Water

Traditional green roofs contribute to pluvial flood mitigation, storing part of the rainwater in the soil substrate and delaying the runoff peak generation (Cipolla et al., 2016; Liu et al., 2020; Mentens et al., 2006; Stojkov et al., 2018; Stovin et al., 2012; VanWoert et al., 2005; Viola et al., 2017). Rainwater is then released to the atmosphere through evapotranspiration processes. Green roof retention capacity depends on many factors, such as soil depth and porosity, vegetation type and antecedent soil moisture (Garofalo et al., 2016). Soil substrate is the main factor that characterizes the green roof retention capacity (Peng et al., 2020): extensive green roofs present lower retention capacity than intensive structures, and the retention capacity generally increases with thicker soil substrates, since more water can be stored and reused for evapotranspiration processes (Viola et al., 2017). Vegetation type

Table 1
Summary of multilayer green roof implications in a WEFE nexus context, including main references and key points. The table should be read as a symmetrical matrix where each row i and each column j represent a field of the WEFE nexus approach. The multilayer green roof implications indicated in this table (vertical text) are the same highlighted in Fig. 2. The diagonal, where each field crosses itself, presents the silo approach, highlighted with a different colour whether it focuses on water (blue), energy (red), food (yellow) and ecosystem (green) independently. The rest of the matrix represents the integrated approach, with an iconic visualization in the upper part of the matrix and with a synthetic description in the lower part. For example, the influence of green roof water-energy interconnection is reported in the cell [i,j] = [2,1] in a descriptive form ("Urban Heat Reduction" and "Hydro-Power") with the main related references, and in cell [i,j] = [1,2] with an iconic representation of the contribution of multilayer green roofs to the reduction of the urban heat island and to the generation of clean energy through the installation of micro-turbines. Cell [i,j] = [2,3], which symbolically illustrates the pollution and energy consumption reduction thanks to local food production on a multilayer green roof, finds the related references in the symmetrical cell [i,j] = [3,2].

	Water		Energy		Food		Ecosystem	
W	Cipolla et al. (2016); Cristiano et al. (2020); Fioretti et al. (2010); Garofalo et al. (2016); Liu et al. (2020); Mentens et al. (2006); Monterusso et al. (2005); Nardini et al. (2012); Paço et al. (2019); Peng et al. (2020); Stojkov et al. (2018); Stovin et al. (2012); VanWoert et al. (2005); Villarreal (2007); Villarreal and Bengtsson (2005); Viola et al. (2017).	Flood Mitigation						
	Aitkenhead-Peterson et al. (2011); Alsup et al. (2013); Czemiel Berndtsson (2010); Gnecco et al. (2013); Gregoire and Clausen (2011); Hashemi et al. (2015); Moran et al. (2003); Vijayaraghavan and Raja (2014)	Water Quality						
	Shafique et al. (2016a); Shafique et al. (2016b)	Rainfall Harvest						
E	Muhammad and Reeho (2017); Poblete et al. (2012); Solcerova et al. (2017); Solcerova et al. (2018)	Urban Heat Reduction	Barrio (1998); Berardi et al. (2014); Kumar and Kaushik (2005); Ouldboukhitine et al. (2011); Polo-Labarrios et al. (2020); Sailor (2008); Sonne (2006); Tang and Zheng (2019); Teemusk and Mander (2009); Zhou et al. (2018)	Thermal Insulation				
	Du et al. (2017); McNabola et al. (2013); Samora et al. (2016)	Hydro-Power	Castleton et al. (2010); Coma et al. (2016); Fioretti et al. (2010); Jaffal et al. (2012); Lazzarin et al. (2005); Maiolo et al. (2020); Niachou et al. (2001); Silva et al. (2016)	Energy Saving				
F	Chao-Hsien et al. (2014); Demuzere et al. (2014); Van Mechelen et al. (2015); Yuan et al. (2003)	Irrigation	(Walters and Stoelzle Midden, 2018)	Local production	Astee and Kishnani (2010); Gaglione and Bass (2010); MacRae et al. (2010); Orsini et al. (2014)	Urban Agriculture		
	Hashemi et al. (2015)	Crops Impact on Water			Walters and Stoelzle Midden (2018); Whittinghill et al. (2013)	Crop Types		
E	Abas and Mahlia (2019); Adugna et al. (2018); Akter and Ahmed (2015); Andenæs et al. (2018); Beckers et al. (2013); Boers and Ben-Asher (1982); Campisano and Lupia (2017); Cipolla et al. (2018); Freni and Liuzzo (2019); Kuntz Maykot and Ghisi (2020); Mahmoud et al. (2014); Mitchell et al. (2007); Molaei et al. (2019); Palermo et al. (2019); Shafique et al. (2016a); Shafique et al. (2016b); Słyś and Stec (2020)	Water Stress Reduction	Davies et al. (2011); Karteris et al. (2016); Li et al. (2010)	CO2 Sequestration	Dieleman (2017); Simons et al. (2006); Simson and Straus (1997); Walters and Stoelzle Midden (2018)	Involving Citizens in Agriculture	Baumann (2006); Benvenuti (2014); Boix et al. (2016); Coffman (2007); Colla et al. (2009); Cranshaw et al. (2010); Fernández Cañero and González Redondo (2010); MacIvor and Ksiazek (2015); Madre et al. (2013); Madre et al. (2014); Williams et al. (2014)	Increase Biodiversity
							Rowe (2011); Speak et al. (2012); Yang et al. (2008)	Air Water Quality
					Colla et al. (2009); Lin et al. (2015)	New Species	Kumar et al. (2019); Lee et al. (2015); Rahman et al. (2015); van den Bosch and Ode Sang (2017); Veronesi et al. (2014)	Human Well-being

can also be a limiting factor for the retention capacity: plants with higher evapotranspiration rates can ensure a faster exchange of water from the soil to the atmosphere (Nardini et al., 2012; Stojkov et al., 2018). Plants characterized by a C3 metabolism ensure high evapotranspiration rates and they are hence preferred to crassulacean acid metabolism (CAM) vegetation. However, some CAM plants, such as Sedum, are largely spread in green roofs since they have shown good retention performance during rainfall events and they are quite resistant to dry periods (Cristiano et al., 2020; Monterusso et al., 2005; Paço et al., 2019; Villarreal, 2007; Villarreal and Bengtsson, 2005). Green roof performance in mitigating flood risk varies depending on the climate conditions (Hellies et al., 2018; Mobilia and Longobardi, 2020; Viola et al., 2017). Viola et al. (2017) investigated green roof retention capacity under four different climate cases, where rainfall and potential evapotranspiration present different behaviour. Results highlighted that the best performance is achieved when rainfall and potential evapotranspiration show the same seasonality during the hydrological year, suggesting that this tool is particularly suitable for areas characterized by intense rainfall events during hot periods. Depending on the climate conditions, however, green roofs can retain between 40% and 80% of the annual runoff generation from the building and thus a good runoff reduction can be ensured also in Mediterranean areas (Fioretti et al., 2010).

Rainwater harvesting tools have been largely used in Mediterranean areas since ancient times. At the beginning, they were used only with the aim of collecting rainwater and reusing it for irrigation or storing it to guarantee a stock for the drinking water supply system of the city (Beckers et al., 2013). More recently, the detention capacity that characterizes these instruments has been used to mitigate pluvial floods. This approach has been developed through the centuries in rural areas and is now commonly used in cities, where rainwater from rooftops is collected and stored in tanks, generally located at ground level (Akter and Ahmed, 2015; Boers and Ben-Asher, 1982; Cipolla et al., 2018; Mahmoud et al., 2014; Mitchell et al., 2007). Rainwater harvesting systems contribute to mitigating pluvial floods, since they enable a large amount of water to be stored during intense rainfall events, reducing the generated runoff (Freni and Liuzzo, 2019; Huang et al., 2015; Mahmoud et al., 2014). In their study on a residential area in Sicily, Freni and Liuzzo (2019) showed that the flooded area can be reduced by up to 35% for rainfall events with a depth of up to 50 mm, by installing rainwater harvesting systems composed of 208 tanks of 5 m^3 in a medium urbanized area of 1.6 km^2. If properly treated, rainwater can be used for domestic non-drinkable purposes, such as home garden irrigation or flushing the toilet (Campisano and Lupia, 2017; Cipolla et al., 2018), and reducing the pressure on the water supply system (Adugna et al., 2018). In areas characterized by long, hot and dry periods, this contribution can significantly improve the water management of the entire city (Molaei et al., 2019). However, rainwater tanks require large volumes, which are not always available in cities. Multilayer green roofs, on the other hand, exploit the volume underlying the green roof to collect water and guarantee a good retention capacity, which ensures pluvial flood mitigation and contributes to the water management in urban areas (Shafique et al., 2016b).

Climate change is projected to increase the frequency of short and intense rainfall events, alternated by long, hot, dry periods (IPCC, 2007; Solomon et al., 2007). The combination of this phenomenon with the constant increase of urbanization, observable in many cities (UN, 2018), leads to the necessity to develop tools that can contribute to a better water management with a sustainable approach (Boller, 2004; Rozos et al., 2013). The water management system needs to deal with pluvial flood risk during intense rainfall events, and at the same time, to cope with water supply system stress during long, hot, dry periods. Thanks to their structure, which combines the retention capacity of green roofs with the storage volume of rainwater harvesting tanks, multilayer green roofs are a promising tool that can support a better water management in urban areas (Andenæs et al., 2018; Shafique et al., 2016a; Shafique et al., 2018), mitigating the climate change effects (Michel et al., 2020) and, hence, contributing to the SDG13 (Climate Action).

In order to reuse harvested rainwater for domestic purposes and for irrigation, it is important to investigate in depth the characteristics of the water. Depending on its quality, it is possible to evaluate different options for reuse. The allowed quantity of chemical and microbiological contaminants is defined in each country with specific regulations and varies based on the water destination. In order to use harvested rainwater for irrigation in urban agriculture, for example, it is necessary to evaluate the heavy metal concentration and the presence of total and faecal coliform bacteria, which could be particularly dangerous to human health (Akrong et al., 2012; Srinivasan and Reddy, 2009). In this case, some specific treatments need to be carefully planned and carried out before using the harvested water for irrigation (Norton-Brandão et al., 2013).

In this framework, it is fundamental to investigate the impact that the multilayer green roof has on the quality of the harvested water. A green roof can act both as a sink and a source of pollution for the rainwater (Gnecco et al., 2013). Although they are designed to improve the water quality (Vijayaraghavan and Raja, 2014), some contaminants could be released from the soil. Hashemi et al. (2015) provided an overview of the origin and concentration of the main pollutants found in the runoff generated from a green roof: the presence of nitrogen, phosphorous and heavy metals is discussed. Nitrogen concentration depends on the soil type and on the fertilizer and different studies highlighted opposite conclusions: in some cases the concentration of nitrogen is higher in the runoff than in rainfall (Aitkenhead-Peterson et al., 2011; Moran et al., 2003), in other cases green roofs act as a sink for this contaminant (Gregoire and Clausen, 2011). Phosphorous concentration in rainfall is generally quite low and its presence in runoff is heavily influenced by the type and amount of fertilizer used. Green roofs perform quite well as a sink for heavy metals, such as Fe, Cu, Al, and Zn, which are retained in the soil layer (Alsup et al., 2013; Czemiel, 2010). Concentration of these contaminants in green roof runoff is lower than in runoff generated from common rooftops (Czemiel, 2010).

2.2. Energy

The fast growth of many cities around the world and the rapid economic development have led to an increase in energy demand (Isaac and van Vuuren, 2009; Jiang and Hu, 2006). In order to meet this demand without worsening the level of pollution and the environmental conditions, it is necessary to find alternative methods to produce clean energy and to develop systems to save energy and reduce its consumption (Midilli et al., 2006; Rosenberg et al., 2013). Ensuring access to affordable, reliable, sustainable and modern energy for everyone is one of the SDGs, which highlights the importance of focusing on renewable energy, especially for transportation and heating (McCollum et al., 2017).

Green roofs play a significant role in the energy balance and saving of buildings: they reduce the direct solar radiation, absorbing 60% of it and reflecting about 20–30% of it (Berardi et al., 2014). Three main phenomena characterize the thermal dynamics of a green roof. Soil and vegetation reduce the surrounding temperature through the evapotranspiration processes. Moreover, vegetation absorbs thermal energy for photosynthesis and acts as a shadow device, protecting the soil from the solar radiation. Lastly, the soil layer presents high heat thermal capacity and low dynamic thermal transmittance, and it creates a good thermal insulation for the building (Berardi et al., 2014). Several studies showed how green roofs contribute to roof insulation (Polo-Labarrios et al., 2020), keeping the temperature constant, and consequently allowing energy to be saved from the heating and cooling systems (Castleton et al., 2010; Jaffal et al., 2012; Lazzarin et al., 2005; Niachou et al., 2001; Tang and Zheng, 2019; Teemusk and Mander, 2009). Sonne (2006) investigated the impact of green roofs on the roof surface temperature in Chicago, showing that, on the hottest day, green roof temperature is 22 °C lower than a conventional rooftop. Similar results were found by Jaffal et al. (2012), who analysed the energy saving that can be achieved with the installation of a green roof in a temperate French climate. In summer, the green roof guaranteed a surface temperature reduction of up to 30 °C. In the same study, the heat flux exchanges between roof and indoor were investigated, showing the insulating effects of green roofs: the indoor air temperature in summer was 2 °C lower and a decrease of 6% of the annual building energy demand was observed.

In Mediterranean areas, Fioretti et al. (2010) explored the attenuation of solar radiation through the vegetation layer and the consequent thermal insulation performance of green roofs, with a significant reduction of the daily energy demand. Similar results are presented in the work proposed by Maiolo et al. (2020), which compares the building energy consumption of an extensive green roof to a traditional one in Mediterranean areas. Under similar climatological conditions, thermal effectiveness of extensive, semi-intensive and intensive green roofs has been investigated in Portugal, through experimental and modelling analysis by Silva et al. (2016). Results showed that the saved heating energy is similar for the three green roof types, but extensive green roofs do not show high performance in saving cooling energy. Compared to traditional black roofs, green roofs enable up to 20% of energy to be saved for extensive solutions and up to 70% for intensive ones.

Besides experimental studies, conceptual and numerical models have been proposed with the aim to support and further develop the results obtained from the field. Several numerical models have been presented to investigate the sensitivity of the thermal insulation to different parameters, such as soil thickness, soil density, vegetation type and leaf area index (Barrio, 1998; Jaffal et al., 2012; Kumar and Kaushik, 2005; Ouldboukhitine et al., 2011; Sailor, 2008). Barrio (1998) presented a mathematical model to investigate the cooling potential of green roofs in summer. In their study, leaf area index (LAI), soil thickness, density and moisture content were identified as the most influent parameter of the soil thermal diffusivity, which increases with the apparent density and decreases with the soil moisture content. In order to achieve the best cooling effect in summer, it is suggested that plants with a large foliage development are selected, ensuring low solar radiation transmission, and that light soils are used. However, these choices might limit the potential thermal insulation during winter: in order to optimize the green roof characteristics to achieve the best performance, both summer and winter times need to be analysed. A physically based model that simulates the green roof energy balance was proposed by Sailor (2008) to investigate the sensitivity of green roof characteristics on the thermal insulation potential. Observations from monitored green roofs located in the United States were used to calibrate the model and investigate the role of soil characteristics and depth, irrigation, plant type, height and LAI on both natural gas and electricity consumption, which heavily depend also on the climate context. Results confirm that a thicker soil layer increases the thermal insulation, reducing heating and cooling energy consumption. Summer electricity saving is guaranteed by a dense vegetation, which, on the other hand, determines a high winter heating energy demand due to the shading effects. The importance of LAI was highlighted also by Zhou et al. (2018), who showed how vegetation with seasonally variable LAI lead to a better annual thermal insulation performance of the green roof than constant LAI. Due to the strong influence of the LAI on the thermal insulation and energy saving, green roofs seem to be thermally beneficial for hot, temperate, and cold climates, which characterize most of the European cities (Jaffal et al., 2012). Extensive green roofs are beneficial for saving energy only in dry and hot periods (Coma et al., 2016), while intensive green roofs can be satisfactorily performing in different climatological regions, including colder areas (Niachou et al., 2001; Teemusk and Mander, 2009).

The additional layer that characterizes multilayer green roofs can provide a supplementary source of potential energy. When the water stored at a high level on top of the buildings is released, it can be used, with the help of small turbines, to generate clean and sustainable energy (Du et al., 2017).

2.3. Food

Worldwide population is projected to reach 9.7 billion by 2050 and 11.2 billion by 2100 (Roser, 2013), and to be concentrated in urban areas, with more than 65% of habitants living in cities (Buhaug and Urdal, 2013; Duranton and Puga, 2014; UN, 2018). The intense urbanization and growth of cities determine a decrease of land available for agriculture (Nugent, 2000), while population growth is leading to a rapid increase in food demand in many countries. This problem can be partially solved with the introduction of urban agriculture in cities: green areas can be, in fact, transformed and used to cultivate different crops (Ackerman et al., 2014; De Zeeuw et al., 2000). Local food production in cities can contribute to lower the pressure on the food supply system, supporting the second SDG (Zero Hunger), which aims to achieve food security worldwide (Blesh et al., 2019).

At the same time, urban gardens are often developed on land close to industrial areas and could absorb pollutants from contaminated soil, such as heavy metals, which are quite dangerous to human health (Antisari et al., 2015; Hu and Ding, 2009; Romic and Romic, 2003; Zhuang et al., 2009). For this reason, multilayer green roofs are a valid support for the urban agriculture, lowering the contamination risk that commonly exists in urban gardens (Gaglione and Bass, 2010; Whittinghill et al., 2013).

Urban agriculture on green roofs could contribute greatly to satisfying food demand. A study in Singapore showed that, if implemented nationwide, rooftop farming could reach 35% of the domestic demand (Astee and Kishnani, 2010), while a simulation in Bologna highlighted how this system could provide more than 12,000 t per year of vegetables, satisfying 77% of the inhabitants' requirements (Orsini et al., 2014). Although urban agriculture on green roofs cannot fully replace the other sources of food, it can be a good support for the local production (MacRae et al., 2010). Some issues, however, need to be evaluated: in particular the thickness of the soil, which is generally less than 15–20 cm, potentially limiting root development and consequently crop production (Whittinghill et al., 2013). On the other hand, a thicker soil layer and heavy plants could determine an excessive weight, which might not be supported by the rooftops, especially in old buildings, where the green roofs were retrofitted. Moreover, the use of fertilizer could imply potential water-quality issues of effluent runoff, with an increase of phosphorus concentration (Hashemi et al., 2015).

As mentioned, many crops present deep-roots and consequently require a thick soil layer, which might not be supported by the roof, while shallow-rooted vegetables, including salad crops such as lettuce, kale and radishes, showed high productivity in extensive systems, requiring minimal nutrient inputs (Walters and Stoelzle, 2018). Whittinghill et al. (2013) investigated the productivity of different vegetables and herbs, generally available in home gardens, on an extensive green roof system in Michigan, where tomatoes (*Solanum lycopersicum*), green beans (*Phaseolus vulgaris*), cucumbers (*Cucumis sativus*), peppers (*Capsicum annuum*), basil (*Ocimum basilicum*) and chives (*Allium schoenoprasum*) were planted. With proper management, which includes irrigation and minimal fertilizer input, all plants, except peppers, survived, showing that urban agriculture on green roofs is possible and productive.

2.4. Ecosystem

The transformation of many areas worldwide from natural to urban had a negative impact on the ecosystem: an increase in pollution and a reduction of green areas has drastically changed the environment, making it hostile and no longer suitable for many species. The installation of green roofs in urban areas could largely contribute to the improvement of the surrounding environment (Li and Yeung, 2014), partially restoring the conditions present before urbanization (Brenneisen, 2006) and fighting air pollution (Carter and Fowler, 2008). Green roofs help to increase biodiversity (Williams et al., 2014), guarantee a better air quality thanks to the CO2 sequestration (Karteris et al., 2016; Li et al., 2010) and provide an added aesthetic value to the city, which have shown to improve human physical and mental health (van den Bosch and Ode, 2017). Many cities worldwide are promoting green roof installation to mitigate the loss of the natural environment, making this tool necessary for a sustainable urban development (Coffman, 2007).

Green roofs have largely shown to be capable of recreating a good habitat for many animal species, including insects and invertebrates (MacIvor and Ksiazek, 2015), pollinators such as urban bees (Colla et al., 2009) and birds (Baumann, 2006; Fernández Cañero and González, 2010). The choice of the plants is very important for the creation of a suitable habitat for different species. The use of native vegetation is generally preferred, although what is considered as "native" vegetation can be questionable (Butler et al., 2012). Benvenuti (2014) investigated the impact of the installation of wildflowers on green roofs, showing that this type of vegetation fits well in an urban environment and contributes to creating a Mediterranean urban ecosystem. Wildflowers facilitate the increase of biodiversity, not only recreating a natural environment for different animal species, but also attracting many pollinators. The potential of the green roof as a habitat for arthropods, such as spiders, true bugs, beetles and hymenopterans, was investigated by Madre et al. (2013) in 115 sites across northern France. Three types of green roof vegetation have been investigated: muscinal, herbaceous and arbustive roofs. Results showed that, due to the more complex vegetation, arbustive roofs attract more species and present an abundance of most of the investigated taxa. In the same green roofs, Madre et al. (2014) investigated the wild plant communities and the variables that shaped their diversity and their taxonomic and functional compositions. An important role is played also by the thickness of the soil layer: a thicker soil substrate ensures suitable conditions for different species also during hot periods, since it generally maintains a necessary level of water content (Coffman, 2007).

Thanks to the additional layer, multilayer green roofs enable the biodiversity to be further increased, attracting different invertebrate and small vertebrate species in the water storage. The humid and not directly exposed to the sunlight environment can recreate the perfect habitat for mosquitos and other insects (Boix et al., 2016; Cranshaw et al., 2010). Although multilayer green roofs constitute a good habitat for many species, their conservation value for rare taxa and other taxonomic groups, especially vertebrates, is poorly investigated and their potential is not comparable yet to ground-level urban habitats (Williams et al., 2014). Industry needs to collaborate with ecologists in order to design more specific tools that can maximize biodiversity gains.

Green roofs, and nature-based solutions in general, can increase the aesthetical values of the city, creating a habitat that can improve human mental and physical health (van den Bosch and Ode, 2017; Veronesi et al., 2014). Although many aspects still need to be investigated in depth with a systematic approach, a strong connection between air pollution, green infrastructure and human health is observable (Kumar et al., 2019). It is, in fact, well documented that air pollution has a negative impact on human health, while urban vegetation can improve the wellbeing (Bell et al., 2004; Mayer, 1999). Depending on the design and policy management, urban vegetation can increase or decrease air pollution, based on the vegetation characteristics (Abhijith et al., 2017). Few studies focused only on the direct impact that green roofs have on air pollution reduction, but all highlighted the high potential of this tool (Rowe, 2011; Yang et al., 2008), even with different vegetation types (Speak et al., 2012). The potential benefits of green roofs on mental human health have been largely investigated: Lee et al. (2015) showed that green roofs increase the worker concentration and attention and are valuable elements for healthy cities and workplaces, while Loder (2014) discussed the influence of different types of vegetation. The installation of green roofs in a commercial area in Malaysia was perceived positively by the citizens, who appreciated the introduction of green areas and are aware of the potential benefits (Rahman et al., 2015). Green roofs can be used in an educational context of children growing up in an urban environment, giving them the opportunity to experience farming and to familiarize with outdoor spaces. An example is given by the green roof built on the East Campus of the Ogden International School of Chicago, where students can gain experience on how food is produced, contributing to some activities such as picking tomatoes from a plant or watching lettuce grow (Walters and Stoelzle, 2018).

3. Nexus approach

From the analysis presented in Section 2, it is clear that most of the studies available in literature investigated the advantages and performances of traditional and multilayer green roofs in relation to one single sector at the time, following a silo approach. The WEFE nexus approach, instead, enables the mutual interconnections and feedback between sectors to be analysed, aiming for a more complete understanding of the phenomenon. In this section, the WEFE nexus approach is applied to the evaluation of multilayer green roof benefits.

3.1. Water-energy

Multilayer green roofs are a key element in the water and energy exchange between the land and atmosphere in the urban context. Vegetation on green roofs largely contributes to cooling the air and reducing the urban heat island (Solcerova et al., 2017). Muhammad and Reeho (2017) investigated the ability of a multilayer green roof to mitigate the urban heat island with a study case in Korea, showing that the surrounding surface temperature was between 5 °C and 9 °C lower with the installation of this tool. Moreover, the water collected in the storage layer can be sprinkled on the streets around the building during the hot and dry days, contributing to the cooling of the temperature (Poblete et al., 2012; Solcerova et al., 2018). This technique, called Uchimizu, derives from a Japanese tradition and can lead to a decrease of the air temperature of up to 6 °C for near-ground level (Solcerova et al., 2018).

Another aspect that characterizes the multilayer green roof in a context of Water-Energy nexus is the accumulation of potential energy connected to the water storage. The water mass stored in the additional layer has, in fact, potential energy since the structure is located at a certain height, on top of the buildings. It is, hence, possible to convert this potential energy into mechanical work and consequently into electricity, with the installation of micro-hydropower systems (Du et al., 2017). The small water turbines are low-cost and easy to install, and they can contribute to the creation of a new and sustainable source of energy (McNabola et al., 2013; Samora et al., 2016).

3.2. Energy-Food

Multilayer green roofs play a significant role in the Energy-Food nexus in an urban context. This tool, in fact, is not only beneficial for the single sectors, increasing the food production and reducing the energy losses, but it can also largely contribute to supporting the interaction between the two systems. The multilayer green roof contributes to achieving the SDG12, which aims to ensure the development of sustainable consumption and production patterns. The local food production, in fact, allows food transport to be reduced, limiting the pollution generated and the energy consumption requested during this process (Walters and Stoelzle Midden, 2018). Moreover, urban agriculture increases the awareness of sustainable food consumption, with a consequent waste reduction.

3.3. Water-Food

Multilayer green roofs can be a valid support to strengthen the Water-Food nexus. Compared to traditional green roofs, multilayer green roofs can store the harvested rainwater for different purposes, including roof garden irrigation, which is necessary for a productive urban agriculture (Demuzere et al., 2014; Waterfall, 2006). The water generally required for urban gardens is derived from the drinking water supply system and the amount is quite higher than the other civil uses. Using the harvested water for irrigation of the soil substrate helps reduce the pressure on the water supply system. Depending on the climate conditions and on the amount of water harvestable, different crops can show the maximum benefits (Yuan et al., 2003). Irrigation during establishment and first growing season is essential in all climates and different techniques to achieve a sustainable irrigation have been investigated (Chao-Hsien et al., 2014; Van Mechelen et al., 2015).

In this context, the multilayer green roof can be seen as an upgraded autonomous version of the traditional one, since it can reuse the stored water for the irrigation of the soil substrate. With a well-organized management of the water storage, it is possible to collect water that can be used to irrigate the green roof itself or, in case of a network of multilayer green roofs, to feed the surrounding tools. In the first scenario a pumping system is required, while in the second case it is possible to create a network of tanks driven by gravity, which does not require any external source of energy.

3.4. Ecosystem – Energy

Urbanization, industrialization and intensity of traffic have led to an increase of carbon dioxide emissions, which constitutes a huge problem for the environment and causes an intensification of cancer and similar diseases. In this context, energy and the ecosystem are strongly related and they need to be investigated together to understand better the problem and identify the potential benefits of the multilayer green roof. Rooftop vegetation reduces the carbon footprint of cities by converting carbon dioxide to oxygen through photosynthesis (Li et al., 2010). Several studies investigated this phenomenon, showing that installing green roofs in urban areas can make a large contribution to reducing the CO_2 emissions (Astee and Kishnani, 2010; Davies et al., 2011; Karteris et al., 2016; Orsini et al., 2014). The CO_2 sequestration capacity depends on the vegetation type, generally varying from 300 gC/m^2 for grasses to 1500 for shrubs (Karteris et al., 2016). Moreover, thanks to the thermal insulation power of the multilayer green roof, CO_2 emissions are also reduced: the limited use of heating and cooling systems contributes to saving energy and protecting the ecosystem (Rowe, 2011).

Vegetation choice is fundamental to ensure a trade-off for both the ecosystem and energy sector. Thermal insulation of the building is, in fact, connected to different development dynamics of leaf canopies. Some vegetation types could be very beneficial for the thermal insulation, but they do not contribute to improving the ecosystem, or vice versa. Wildflowers, for example, have a great impact on the ecosystem, attracting insects and pollinators, but they do not guarantee high performance for thermal insulation (Benvenuti, 2014).

3.5. Ecosystem – Food

As mentioned, multilayer green roofs can be used as a support tool for urban agriculture and at the same time they can recreate a natural habitat for many species, including bees and other pollinators, which are necessary for plant survival (Colla et al., 2009). Hence, there is a strong connection between urban agriculture and the ecosystem, which needs to be analysed in depth when installing a green roof (Lin et al., 2015). The vegetation choice, that can ensure food production and biodiversity increases, needs to be carefully evaluated. Orsini et al. (2014) investigated the potential of vegetable production on the rooftops in Bologna (Italy) in relation to the citizens' needs, analysing also the improvement of urban biodiversity through the creation of green corridors. Moreover, horticulture is recognized as a good alternative therapy that can facilitate mental health (Simson and Straus, 1997) and fight dementia (Simons et al., 2006). A similar study has been carried out in Mexico City, where urban agriculture is widespread, and 20% of the food production is derived from it (Dieleman, 2017). Besides the economic benefits, this work highlights the social and health improvements of increasing the capacity building, teaching to the citizens the principles of hygiene in food processing and the proper use of organic wastes and wastewaters.

3.6. Ecosystem – Water

As mentioned before, collected rainwater can be used for different domestic purposes, such as home garden irrigation or flushing the toilet, for which drinkable water from the supply system is generally used (Adugna et al., 2018; Campisano and Lupia, 2017; Cipolla et al., 2018; Słyś and Stec, 2020). The pressure on the water supply system could be, hence, reduced (Abas and Mahlia, 2019; Kuntz Maykot and Ghisi, 2020; Palermo et al., 2019), contributing to an increase in drinkable water for everyone. This is in line with the SDG6, which promotes a sustainable management of water and sanitation that ensures water availability (Ortigara et al., 2018). Moreover, if the drinking water request is low, the need for new raw-water collection infrastructures and pipe networks decreases. In this way, the anthropogenic impact on the natural environment is limited, with consequent benefits for the ecosystem.

Campisano and Lupia (2017) investigated the potential water saving achievable with the introduction of rainwater tanks to collect water and reuse it for toilet flushing and home garden irrigation in Rome (Italy). Results pointed out that the water saving reaches 38–65% for tank sizes within 1–50 m^3. Similar results were presented by Cipolla et al. (2018), who simulated the potential water saving in 4 flats of a building located in Bologna for 13 years. In this case, the water saving efficiency was about 75%, which accounts for 26.71% of the mains water withdrawal.

4. SDGs

As mentioned in the previous analysis, the multilayer green roof is a powerful tool, which can be beneficial in different fields, and can contribute to the sustainable development of cities. The urban-scale application of this new and original technology will contribute to the development of the industry (SDG9: Industry, innovation and infrastructure), with the identification of innovative materials and techniques, which will guarantee an intense, but at the same time sustainable, production. The green roof industry development is aligned with the Green Deal policy, which focuses on the sustainable development of the economy, and it will create new job opportunities, facilitating economic growth (SDG8: Decent work and economic growth). Moreover, new partnerships will be born to improve this technology (SDG17: Partnership to achieve the goal), exploring new materials and techniques that can be used to increase the performance of this tool and to make it more sustainable and eco-friendlier (Bianchini and Hewage, 2012). Multilayer green roofs were originally proposed as a tool to fight against climate change effects (SDG13: Climate Action), contrasting the urbanization through the installation of green spaces on the rooftops. This instrument contributes to reducing the urban heat island and is a valid support in mitigating pluvial floods. Moreover, harvested rainwater can be reused for several domestic purposes, reducing the pressure on the water supply system and consequently increasing the availability of drinkable water for everyone (SDG6: Clean Water and Sanitation). Thanks to the potential applicability of urban agriculture on its surface, multilayer green roofs can reduce the population food demand (SDG2: Zero Hunger), especially in poor countries, where many people have limited or no access to food. In this context, the local food production should lead to a responsible consumption (SDG12: Responsible Consumption and Production), lowering the waste and limiting the CO2 emissions due to food production and transport. Thermal insulation power of green roofs ensures a reduction of the energy consumption for heating and cooling systems, partially constituting a new source of clean energy (SDG7: Affordable and Clean Energy). The installed vegetation will support the increase of biodiversity, attracting many animals, including insects, small vertebrates and pollinators, which are fundamental to guarantee maintenance of the ecosystem (SDG15: Life on Land). This tool recreates a good habitat for many species and can improve also the human habitat, since it contributes to the mental and physical well-being of citizens (SDG3: Good Health and Well-being). With all these potential benefits in a WEFE nexus context, a large-scale implementation of the proposed solution could contribute to the creation of sustainable and resilient urban areas (SDG11: Sustainable Cities and Communities).

5. Conclusions

This work presented a review of benefits and limitations of green roofs, with a special focus on multilayer green roofs, which, compared to the traditional ones, can collect the percolated water in an additional storage layer. These tools are analysed with an integrated Water-Energy-Food-Ecosystem nexus approach, which enables to fully evaluate and understand the potential of this technology in an urban context. While with the traditional silo approach only one sector is investigated, the WEFE approach investigates the potential impacts of the installation of multilayer green roofs on different sectors, aiming for a complete understanding of the dynamics. At first, the role of green roofs in relation to the water, energy, food and ecosystem sectors has been analysed separately and in a second step the interconnections between the different fields have been highlighted and discussed.

Main findings and related references available in literature are summarized in Table 1: studies based on a silo approach are highlighted on the diagonal of the table, while on the lower part, the integrated analyses are reported which exploit the WEFE nexus approach. From the table, it is clear that most of the studies up until now have focused on a silo approach, although only integrated approaches allow all the benefits of multilayer green roofs to be investigated and their limitations to be understood. Without the WEFE nexus approach, it would not be possible to fully evaluate the impacts of this tool on the sustainable development of cities and communities.

The analysis of the available scientific literature showed how multilayer green roofs can be a valid support for the creation of smart and resilient cities, being beneficial in different ways for the WEFE sectors. In the last decades, cities have been observing a complex development characterized by fast and global changes: the population is growing, the level of urbanization is increasing and the climate is rapidly changing, with a general worldwide-temperature increase and an intensification of extreme rainfall events. In this context, the installation at urban scale of multilayer green roofs will offer potential solutions for these multi-sectorial problems. This tool can, in fact, support the pluvial flood mitigation, reduce the heat island, contribute to the building energy saving, increase the biodiversity and add aesthetic value to the city. With a strategic management, the large-scale installation of multilayer green roofs can reduce the pressure on the water supply system and provide food from the urban agriculture. On the other hand, multilayer green roofs present also some limitations: in historical city centres, for example, not all the roofs might be suitable for the installation of these tools, and a careful structural analysis needs to be carried out before the installation. Moreover, particular attention needs to be given to the choice of soil thickness and vegetation type: water retention capacity, building energy saving, food production and biodiversity increase depend on the choices of the designer. It is hence, fundamental to evaluate through an integrated analysis, such as the WEFE approach, all the implications that the choice of soil thickness and vegetation type can have on the different sectors. Benefits and limitations can only be understood and correctly evaluated with an integrated multi-sectorial approach, such as the WEFE nexus analysis.

Finally, multilayer green roofs largely contribute to many Goals of the 2030 Agenda for a Sustainable Development, highlighting the key role that they could play in a sustainable development of the urban areas. The installation of this tool, in fact, can have a positive effect on 11 out of the 17 Sustainable Development goals (SDG 2, 3, 6, 7, 8, 9, 11, 12, 13, 15 and 17), improving at the same time the environmental quality and human wellbeing. In a context of global changes, the multilayer green roof represents a strategic tool that can adapt to the fast evolution of the city following a sustainable and smart path.

In conclusion, this study underlined at the same time how green roofs, and in particular multilayer ones, are powerful tools for the creation of sustainable and resilient cities and how the WEFE nexus approach is an essential method to support this type of analysis.

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Declaration of competing interest

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