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Decentralized rooftop and container agriculture using greywater and fog harvesting: a feasible strategy for water–food–energy security in mediterranean urban environments

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Achieving the Sustainable Development Goals in urban environments, such as zero hunger and agriculture and food security, requires strategies that increase food and biofuel production without adding extra pressure on urban freshwater resources. This study aims to evaluate the feasibility of rooftop and container agriculture in Mediterranean urban environments using two alternative water sources, including domestic greywater and atmospheric fog harvesting. Maize and sunflower are studied as strategic multipurpose crops due to their suitability for selected systems, adaptability to urban microclimates, and double applications in food and biofuel production. The analysis includes an assessment of urban cultivation areas, fog harvesting potential, greywater quality, and selected crop water requirements, besides the importance of simultaneous consideration of food and energy security. Moreover, the detection methods for suitable areas, the potential rooftop and garden agriculture in some case studies, and the feasibility analysis of urban farming in rooftop and container agriculture using fog and greywater has been explored. Results indicate that domestic greywater, produced continuously within households, can satisfy the full irrigation demand for both crops across the entire growing season, while fog harvesting can supply a maximum value of 28% for sunflowers and 34% for maize water requirements. Moreover, the analysis determined that fog water is suitable for direct irrigation, whereas greywater may be used directly for biofuel-oriented agriculture or applied to food crops following a pre-treatment. In conclusion, the investigation demonstrates that combining fog harvesting with greywater reuse provides a practical and decentralized approach to support urban agriculture for multipurpose crops, enhance local food and energy resilience, and reduce dependence on potable-water networks.

KEYWORDS

biofuels, climate change, energy security, fog harvesting, food security, grain

1 Introduction

Urban agriculture refers to the cultivation, processing, and distribution of food and non-food crops within or around cities (Dobele and Zvirbule, 2020). It can include rooftop farming, balcony or container cultivation, community gardens, and peri-urban agricultural zones (Grard et al., 2018). It can integrate food production into the urban environment and contribute to food security, resource efficiency, and environmental sustainability by utilizing new spaces and alternative water sources (Langemeyer et al., 2021). Within this framework, maize and sunflower are considered strategic multipurpose crops because they simultaneously address food security (human and animal consumption) and energy security (bioethanol and biodiesel production). Maize is one of the world's major grains for human consumption and animal food (Erenstein et al., 2022), and is also a key feedstock for bioethanol production (Bello et al., 2022). In addition, sunflower is a valuable crop for providing high-quality oilseed as well as biodiesel production (Khan et al., 2023).

Their high adaptability, relatively short growing cycles, moderate root depth, suitability for container or rooftop cultivation, and dual food–biofuel value make them ideal candidates for improving the Water–Food–Energy (WFE) nexus in Mediterranean climates.

Therefore, in this section, we first analyze the various atmospheric water harvesting techniques, greywater properties, and the potential for urban agriculture as two alternative water sources to not put any pressure on the urban drinking water network. Then we analyze the properties of greening systems in the urban environment and investigate the possibility of urban agriculture and the characteristics of maize and sunflower for this purpose. In the next step, we study the vulnerability of food and energy and the role of urban farming with multipurpose crops for biofuel and extra food production.

1.1 Various atmospheric water harvesting techniques

In many locations, the water demands of plants in summer (during the growth period) cannot rely just on precipitation (Nektarios, 2018). Harvested rainwater from roofs and atmospheric water generation are two alternative water sources that can be used in the urban environment. Nevertheless, in areas with dry and semi-dry climates and even in the Mediterranean climate with high annual rainfall (>1000 mm), the precipitation in summer is usually very low or even Zero (Pirouz et al., 2020c); therefore, there will be no rainwater harvesting as well.

However, the investigation shows the potential of atmospheric water harvesting (fog and dew) in many geographical regions, especially in dry seasons (Beysens et al., 2007). Salem et al. investigated the feasibility of using fog water harvesting (quantity, quality, and economic) for irrigation purposes in Egypt. The TDS (Total dissolved solids), SAR (Sodium adsorption ratio), and heavy metals (Cd and Pb) analysis of the collected water were suitable for various plants, and the cost of the unit was relatively low (Salem et al., 2017). In another study, Abdul-Wahab et al. analyzed the fog water harvesting quality in Oman, which determined the suitability of the water for different purposes (Abdul-Wahab et al., 2007). Gandhidasan and Abualhamayel analyzed the quality of fog harvesting at two sites in Saudi Arabia, and the results showed good quality based on WHO guidelines for drinking water (Gandhidasan and Abualhamayel, 2012).

The fog harvesting potential could be increased by using a simple hydrophilic coating mesh (Liu et al., 2020). Using other methods, such as collecting the condensate, the balance between the water and energy footprint must be considered. However, innovative materials and designs are increasing the water uptake efficiency in the next-generation atmospheric water harvesting systems (AWH) (Zhou et al., 2020).

Another important factor that must be considered when using fog harvesting mesh is the negative impact of trapping birds and animals. In this regard, wildlife-friendly products with specific mesh (size and color) could decrease the negative impacts.

1.2 Greywater potential for urban planting

Another alternative water source in urban environments could be Greywater (GW), which is around 70% of the building's wastewater (WW). It comes mainly from bathrooms, laundry, showers, and sinks (except toilet flushes), and its quality makes it an ideal source for non-drinkable reuse, such as green roofs (Glover et al., 2021). Khanam and Patidar classified different parts of Graywater and found that the highest pollution comes from the kitchen and laundry (Khanam and Patidar, 2022).

Using greywater for irrigation could be confronted with some hazards due to the presence of organic and chemical compounds (Turner et al., 2016). However, green roofs and green walls are considered new methods for greywater treatment and reuse (Boano et al., 2020). Green roofs can be used for the treatment of urban wastewater, especially for nitrate, phosphorus, and total suspended solids (Piro et al., 2011; Liu L. et al., 2021). In addition to green roofs and green walls, bioretention facilities (such as rain gardens and biofiltration cells) are other effective Nature-Based Solutions (NBS) for the treatment of urban runoff and wastewater (Jessup et al., 2021). These systems are widely reported to achieve significant removal of nitrate, phosphorus, and total suspended solids (TSS) (Søberg et al., 2021). In urban environments, bioretention facilities can operate in synergy with green roofs by runoff and greywater treatment, increasing the pollutant removal efficiency and reducing the pressure on wastewater treatment plants (Zhang et al., 2022).

Peri-urban agriculture by wastewater irrigation has been investigated in many studies (Singh and Sharma, 2021; Zolfaghary et al., 2021), and it was determined that the associated health risks in food production are manageable (Starkl et al., 2013), since the contaminants in domestic wastewater can be determined with high accuracy (Wang et al., 2020). Nitrogen and phosphorus are the main contaminants in domestic wastewater (Batstone et al., 2015). Moreover, irrigation by wastewater could improve plant growth significantly (Liu C. et al., 2021), and can prevent the consumption of chemical fertilizers (Zhang and Shen, 2019). Disha et al. analyzed the greywater parameters for irrigation, and their results show that a pre-treatment process seems necessary due to some contamination in greywater, mainly TSS and bacterial pollution. The pre-treatment they used included screening to remove coarse materials, solar disinfection (by keeping the samples in sunlight for around 6 hours), and improved oxygen saturation (Disha et al., 2020). However, the characteristics of greywater are influenced by several factors, including the number of residents, cultural habits, living standards, the quality of the water supply, etc. (Porob et al., 2020). In addition, the cost of natural greywater treatment on small scales, such as apartments and multi-home, is low (Boano et al., 2020).

1.3 Greening systems and the potential of urban agriculture

Greening systems, such as green roofs, present several advantages, such as water quality improvement (Pirouz et al., 2020a), stormwater management (Pirouz et al., 2020a), urban life quality (Manso et al., 2021), improving thermal behavior of buildings (Maiolo et al., 2020), decrease of water footprint of energy (Pirouz et al., 2020b), and heat island mitigation (Koch et al., 2020). Green roofs are typically distinguished based on the soil layer's depth, as an Extensive Green Roof (EGR) is with a depth larger than 15 cm, and an Intensive Green Roof (IGR) with a depth of less than 15 cm (Hossain et al., 2019).

The potential of urban agriculture is increasing year after year, mainly due to the increase in population, land use limits, lack of cultivation space, food insecurity, and climate change impact (Tornaghi, 2017; Taylor, 2020; Yan et al., 2022). Orsini et al. analyzed the production capacity of urban agriculture in Bologna (Italy) (Orsini et al., 2014). They first calculated the total flat roof surfaces and the possibilities of green corridors. They determined the feasibility of producing about 77% of the inhabitants' vegetable requirements from a new agricultural area of 82 ha. This and other case studies refer to urban agriculture (UA), rooftop vegetables (Orsini et al., 2014), urban farms (Pulighe and Lupia, 2019), home gardens (Sanyé-Mengual et al., 2018), peri-urban agriculture (Zezza and Tasciotti, 2010), and decreasing the fresh vegetable market cost and GHGs by UA (Lee et al., 2015).

1.4 Maize and sunflower as two strategic plants

Maize (Zea Mays), whose origin is Central America, is the most important cereal for human and animal consumption. Maize can grow in different climates, and successful cultivation depends on the variety (FAO, 2015; Wu et al., 2021). The recommended depth of maize seeding is 3.8–5.1 cm (University of Missouri, 2016). The average root length is about 74 cm, and root penetration is about 0.2 m (Hossne G. et al., 2016) to 0.3 m (FAO, 2015).

Therefore, the ideal rooftop bed or container for maize is about 20–30 cm (Massonneau, 2012; Dubbeling and Massonneau, 2014). The corn yield exhibits significant variations. It is about 11.8 tons per hectare in the US (USDA, 2014; Association, 2019), 11.94 tons per hectare in Italy (Pulighe and Lupia, 2019), and 5.56 tons per hectare in Ukraine (Dukhnytskyi, 2019). One bushel of corn (≈25 kg) can produce about 7.7 kg of animal food (3.6 kg beef, 7 kg pork, 9.8 kg chickens) or 10.6 L of ethanol. The harvesting time of corn is from 9 to 18 weeks, depending on the climate (Ministry of Food Production, 2013; Gu et al., 2017).

Sunflower (Helianthus annuus L.), whose origin is in the US, has an important commercial value (vegetable oil and biodiesel) (Ragaglini et al., 2011; Seiler and Gulya, 2015). Analysis of four sunflower cultivars in Brazil showed an average annual yield of 1,516 kg ha^{-1} (41% oil content equal to 594.4 kg ha^{-1}) (Brazil et al., 2019). Ragaglini et al. analyzed the potential of biofuel production by sunflower in Tuscany (Italy), where about 345,685 ha could be available for sunflower cultivation, and determined that the total annual yield could be 95,000 tons (equal to 26,500 TOE/year of fossil fuel) (Ragaglini et al., 2011). The results of another study in Central Italy determined a sunflower production yield of 5.29 tons per hectare and oil yield as bioenergy for high-oleic varieties, around 35% of seed weight, meaning as high as 1,850 kg ha^{-1}(Barontini et al., 2015).

The sunflower's average plant height is about 185 cm, and its head circumference is about 20 cm (Brazil et al., 2019). Sunflower's water sensitivity is less than maize's (FAO, 1991). Maize and sunflower root penetration lengths that make the container and rooftop cultivation possible are shown in Figure 1.

The selection of maize and sunflower as strategic multipurpose crops is supported by their global agronomic relevance, high nutritional and energy value, and suitability for decentralized cultivation. Both crops have a relatively short growing cycle, moderate root penetration depth, show good drought tolerance, adaptability to urban microclimates, and compatibility with alternative water sources such as fog harvesting and domestic greywater. Their dual role in food and energy production, combined with their suitability for urban agriculture, makes maize and sunflower highly appropriate as strategic plants for enhancing urban resilience within the Water–Food–Energy nexus.

1.5 Food and energy security and the role of urban farming with strategic plants

Another vital element in urban agriculture analysis is improving food security, an important Sustainable Development Goal (SDG). There are several limits to increasing food production, including the steady growth of cities with decreasing open and green spaces (Ring et al., 2021) and climate change that affects agriculture (Dorward and Giller, 2022). Europe and Central Asia, North America, Latin America, and the Caribbean are among the net exporters of agricultural commodities, whereas Asia Pacific, the Middle East, North Africa, and Sub-Saharan Africa are among the net importers. Since 2016, Russia has been the largest wheat exporter, Ukraine the fifth, and Kazakhstan the ninth. In addition, Ukraine and Russia are among the top five maize exporters (Agricultural Outlook, 2021-2030, 2022). According to estimates by OECD-FAO, by 2030, the European Union will be the second exporter of wheat, with 14% of global exports (after Russia with 22%), and the main exporter of other coarse grains (without consideration of wheat, maize, and rice), it is also the main importer of maize, 11% of total global trade (FAO, 2020). Russia, Ukraine, and Kazakhstan are among the major players in global grain markets (Fellmann et al., 2014) and belong to the World Trade Organization (WTO), Ukraine since May 2008, Russia since 2012, and Kazakhstan since 2015 (WTO, 2015).

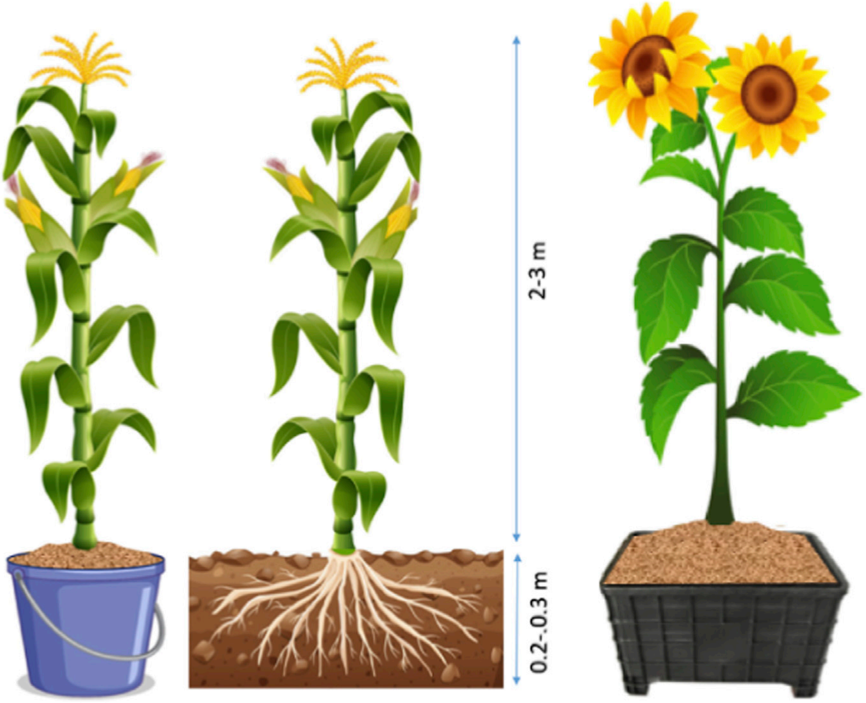


FIGURE 1
Maize and sunflower root penetration lengths and container cultivation.

According to the WTO, Russia and Ukraine are key suppliers of energy, food, and fertilizers (WTO, 2022). Therefore, world trade suffering from COVID-19 is again disrupted due to the Russia-Ukraine crisis and the halt of grain shipments through Black Sea ports.

In addition to food security, global energy vulnerability is another important element that can be addressed through biofuel in urban agriculture. Biofuels are related to several SDGs, such as SDG 13 (climate change impact) and SDG 7 (sustainable energy) (Acheampong et al., 2017). Production and use of biofuels, such as crop and food wastes, can decrease greenhouse gas emissions (Paul et al., 2019). Biofuel sources can be various, from oil, such as palm oil, biological mechanisms by microorganisms on wastes, ethanol from grains (i.e., corn), sugars or fats, and biomass production from algae (Acheampong et al., 2017). Moreover, corn stover (CS) can be used for both energy (biogas) and, production of cellulosic ethanol, and nutrients (liquid fertilizer) (Paul et al., 2019). Several prospects exist for corn's use in the US as a biofuel basis (Moore et al., 2016).

Zhao et al. investigated heavy metal concentrations in sunflower biofuel planted in marginal urban lands (Zhao et al., 2014). The results showed that the biofuel produced could have negative environmental and health impacts. Moreover, they determined the average sunflower seed yield according to GTECH (Growth Through Energy and Community Health) to be about 280 kg ha^{-1}, which agrees with the result of Ragaglini et al. ref. (Ragaglini et al., 2011).

The trend of biofuel production has been increasing, especially since 2006, mainly in the US and Brazil (Turrio-Baldassarri et al., 2004). However, biofuel production also has negative impacts. The key concerns are food security and risks in changing land use (IRENA, 2012). For example, the US doubling of ethanol corn production between 2004 and 2007 removed about 57 million tons of corn from the global food supply (Senauer, 2008).

While bioethanol could be an important option for energy security, increasing food prices puts it ahead of food security. The results of a simulation in China for the Maize price index by 2030 show the diverse impact among the production trend of cereal (as maize is the main component of cereal production) and bioethanol (as maize is one of the main feedstocks for bioethanol production). The bioethanol promotion policy could raise the maize imports by China and increase the world maize price index by 5% (Han et al., 2022). Bioenergy production must not negatively affect other sectors. One way is to consider it as a part of the bioeconomy, which means the application of the planted maize for agriculture, fisheries manufacturing (i.e., food, paper, wood), chemicals, and medicines production, besides biofuels (IRENA, 2012).

The Water–Food–Energy (WFE) Nexus highlights the interdependencies among sectors, where increasing demand in one sector may create pressures in the others (Ali and Acquaye, 2024; Javan et al., 2024). For example, producing more freshwater, particularly in an urban environment, typically requires additional energy (also indirectly with the water footprint of energy), while expanding food production increases both water and energy usage. Analysis of previous studies shows the advantages of greening systems in urban environments and the importance of a balance between bioenergy and food security, and the selection of the best crops for this purpose and feasibility analysis in urban environments. However, despite the growing literature on greywater reuse, green roofs, and atmospheric water harvesting, current approaches mostly include conventional irrigation systems,

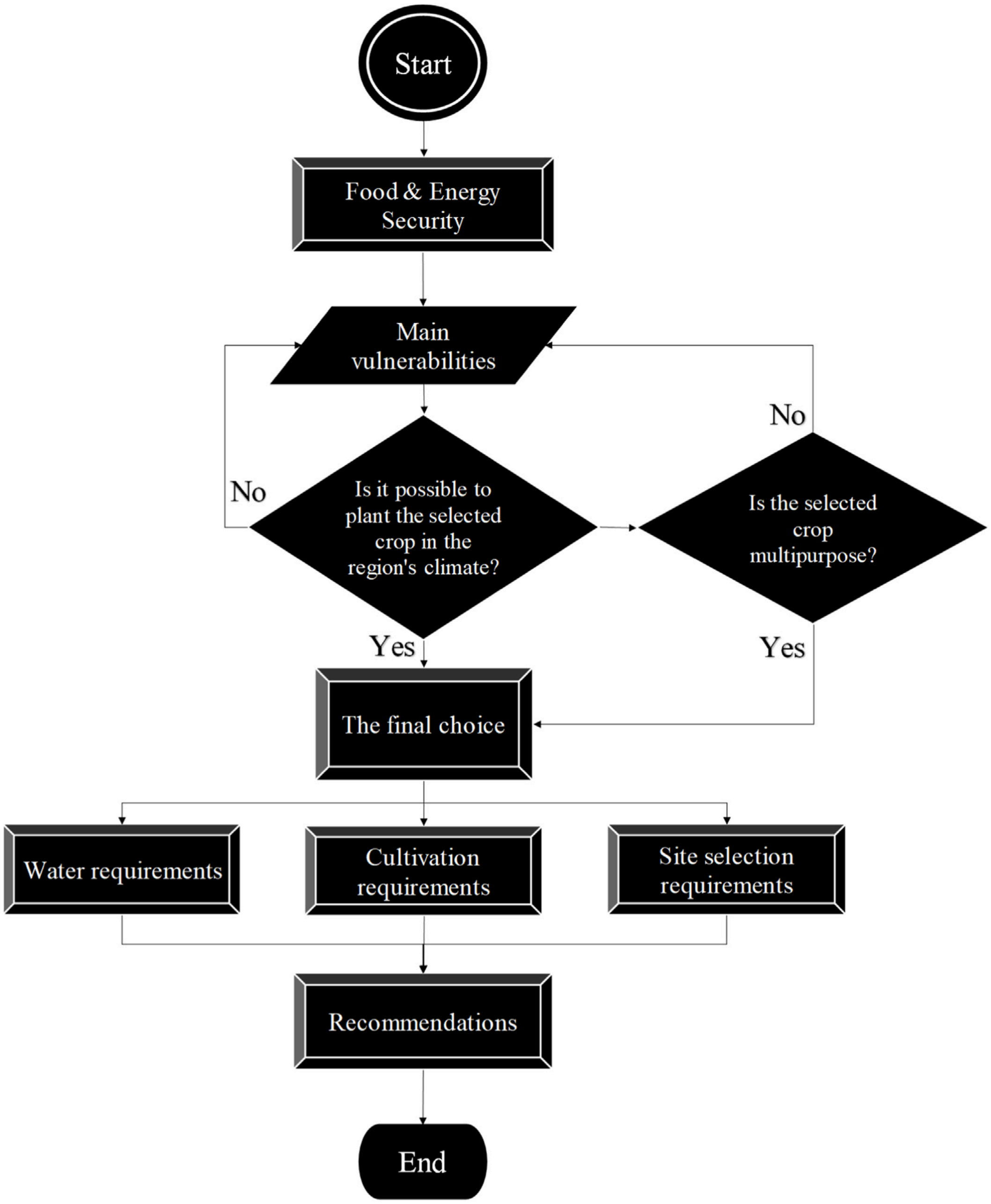


FIGURE 2
Flowchart of the proposed decentralized Water–Food–Energy system.

dependence on urban water networks, and there is a significant gap in integrating the methods into one scalable system for urban agriculture. Moreover, in previous studies, less attention has been devoted to analyzing a combined system using fog harvesting/ domestic greywater for strategic plants (such as maize and sunflower). In this regard, our study aims to develop a system to decrease the vulnerability of global food and energy security, including practical ways to increase the feasibility of rooftop and container agriculture using atmospheric water harvesting/domestic greywater. The novelty of the method lies in the hybrid water supply strategy (combined use of two alternative water sources) in the Mediterranean climate during summer, in which precipitation is near zero, and in demonstrating the technical feasibility of supporting crop cultivation without increasing pressure on urban water networks.

2 Materials and methods

The analysis flowchart is shown in Figure 2.

According to the conceptual flowchart, the issue of food and energy security in a selected region needs to be checked out first to determine the strategic multipurpose plants for both food and energy production. Therefore, the possibility of improving the

TABLE 1 Water requirement of maize in a total growing period of 80–110 days and sunflower in a total growing period of 125–130 days.

Grain	Case study	Climate	mm/Total growing period	Ref.
Maize	Different case studies	Different climates	500–800	FAO (1991)
	Zimbabwe	Subtropical	845.8	Rahman et al. (2016)
	Maiduguri (Nigeria)	Hot semi-arid	736	Tekwa and Bwade (2011)
	Egypt	Desert	472–633	Karrou (2012)
	Thailand	Tropical	375.6	Gheewala et al. (2014)
	New Mexico (US)	Continental	693.4–1,140.5	Djaman et al. (2018)
	Guangzhou (China)	Humid subtropical	470–488.5	Tan and Zheng (2017)
Sunflower	Different case studies	Different climates	600–1,000	FAO (1991)
	Zimbabwe	Subtropical	755.6	Rahman et al. (2016)
	South Africa	Warm temperate	471–582	Netshifhefhe and Jordaan (2022)
	Ghana	Tropical humid-coastal	672.4	Yawson et al. (2011)

situation and the feasibility of creating new planting areas for urban agriculture needs to be investigated. Moreover, in this stage, other necessary analyses would be on the cultivation and water requirements of the selected plants. In this regard, to not put pressure on the urban water networks during the plant growth period in summer, in dry and semi-dry climates, and even in the Mediterranean climate, the precipitation in summer is usually very low or even zero, looking for the possibility of alternative water sources seems necessary. Two alternative water sources could be greywater and fog harvesting potential, which depend on the climate type and case study conditions.

After a literature review, we selected two crops, maize and sunflower, as strategic plants for our feasibility analysis. Sunflower is used for oil and biofuel, and maize is used for human and animal food, besides oil and biofuel production. Now, let us analyze the water requirements during the growing period and the feasibility of using greywater and atmospheric water harvesting for irrigation purposes in urban agriculture.

2.1 Water requirements of maize and sunflower

While the irrigation of the plants would be according to the humidity sensors in the soil based on the water tension, indices like the Water Requirement Satisfaction Index (WRSI) can be used for initial calculations of the water requirement (Senay and Verdin, 2002; Masupha and Moeletsi, 2020):

$$WRSI = \frac{AET\ (actual\ evapotranspiration)}{WR\ (crop\ water\ requirement)} \times 100 \tag{1}$$

$$WR = ET_0 \times K_c, ET_0 : \text{Reference evapotranspiration } K_c : \text{Crop coefficient} \tag{2}$$

Table 1 presents water requirements for the total growing period of maize and sunflower, as suggested by different case studies under diverse climate conditions. The mean values are 500–800 mm for maize and around 600–1,000 mm for sunflowers. Another solution in an urban environment may come from increasing drought tolerance due to existing methods to improve it, such as Carbon Dots (CDs) (Yang et al., 2022).

2.2 Feasibility of using greywater and atmospheric water harvesting

Although rainwater harvesting systems, such as rooftop harvesting tanks and rain barrels, are commonly considered an additional source of irrigation water in urban agriculture, their applicability depends strongly on local climatic conditions. In the Mediterranean climate of the study area with high annual rainfall (>1000 mm), the precipitation in summer is usually very low or even Zero (Pirouz et al., 2021), and the Bagnouls–Gaussen diagram, derived from historical data from the Cosenza station (1914–2019), shows a water deficit from May to September, which coincides with the growing period of maize and sunflower. As a result, summer precipitation is extremely low or effectively zero, making rainwater harvesting insufficient for meeting irrigation needs. For this reason, while rainwater harvesting is a valuable decentralized water source in many regions, it cannot serve as a reliable or sufficient irrigation source in this specific Mediterranean case study. In this regard, this section analyzes the possibilities of using domestic greywater and fog harvesting to irrigate the selected plants. In the case of contamination, safe production should be for biofuel, not domestic food.

The analysis by Estrela et al. in different locations with Mediterranean climates shows the fog harvesting potential from 1.6 to 4.6 L/m^2 in the summer (Estrela et al., 2008). Another study by Bitonto in Italy (Milan) with elevations more than 120 m shows a value of about 3.3 L/m^2 (Bitonto et al., 2020). The fog harvesting potential in different climates is presented in Table 2. As presented in Table 2, the potential of fog harvesting exists even in deserts, but it also depends on other factors such as elevation, distance from the seashore, and mesh characteristics, and it could range from 1.8 to 75 L/m^2. The feasibility of using atmospheric water harvesting in different climates has been discussed in detail in previous studies by

TABLE 2 Fog water harvesting potential in different climates.

Climate	Case study	Elevation [m]	Fog harvesting potential [L/m^2/fog day]	Ref.
Mediterranean	Italy	120	3.3	Bitonto et al. (2020)
	Spain	670–1,193	2.9–7.3	Estrela et al. (2008)
	Spain	—	10–40	Ritter et al. (2015)
	Morocco	1,225	10.5	Dodson and Bargach (2015)
	Canary Islands	—	9.5	Marzol and Megía (2008)
	Different locations	—	1.6 to 4.6 summer	Estrela et al. (2008), Pirouz et al. (2021)
Sub-tropical	Nepal (Katmandu)	1,400	1.8	FogQuest (2020)
	Oman	—	875.85 L/m^2 (July to September)	Abdul-Wahab et al. (2007)
Tropical	Guatemala	3,300	3.75–4.17	Klemm et al., 2012; Tony (2020)
Desert	Cape Verde	750–1,400	3 to 75	Sabino (2007)
	Saudi Arabia	—	64–78 L/m^2 (December to March)	Gandhidasan and Abualhamayel (2012)
	Chile (Coastal area)	—	7	Cereceda et al. (2008)
Arid tropical	Peru	800	11.8	Fessehaye et al. (2014)

TABLE 3 Characteristics of domestic greywater in some case studies.

Case study	Rate [L/PE/day]	pH	TP* [mg/L]	TN** [mg/L]	TDS [mg/L]	TSS [mg/L]	Ref.
France	Total 170	7.3	—	—	—	59	PLAT et al. (2019), Boano et al. (2020)
Australia	—	—	3	5.3	—	74	Boano et al. (2020)
Spain	Total 130	7.4	-	16.2	—	336	Gattringer et al. (2016), INE (2018)
Germany	Total 117	7.6	15.2	1.6	—	—	Ghaitidak and Yadav (2013), PTC (2016)
Bangladesh (untreated)	—	7.07	—	—	522	114	Disha et al. (2020)
Bangladesh (treated)	—	7.02	—	—	563	53	
Europe average	GW 100-150	—	—	—	—	—	Ghaitidak and Yadav (2013)
Developed countries	GW 88-200	6.7–9.03	2.8–17.7	9.7–47.8	—	—	Khanam and Patidar (2022)

* TP: total phosphorus.
** TN: total nitrogen.

Pirouz et al. (Pirouz et al., 2020c; 2021). Therefore, fog events, while insufficient as the only water source (as limited in volume), typically occur during early mornings and evenings in summer and late spring, align well with the growing season of maize and sunflower, and can serve as a supplementary water source.

Characteristics of domestic greywater in some case studies are presented in Table 3. In developing countries, out of the total daily graywater, 88–200 L/PE/day, the average laundry-water contribution accounts for about 13–85 L/PE/day, the kitchen for 12–63 L/PE/day, and the shower and handbasin for between 33 and 90 L/PE/day (Khanam and Patidar, 2022). The average greywater quantity in Greece shows that from the total wastewater of 132 L/PE/day, about 72.5% belongs to greywater, and 35% is light greywater (Noutsopoulos et al., 2018). Another study determined that the daily GW based on population equivalent (PE) in Europe is around 100–150 L/PE (Ghaitidak and Yadav, 2013).

Therefore, it is possible to consider fog harvesting and greywater for urban farming as alternative water sources without putting pressure on the urban drinking water network. The comparison will be carried out by considering maize and sunflower water consumption during the growth period and the potential of the mentioned water source.

2.3 Image processing to detect the suitable area for urban farming

The detection methods, such as image processing for analysis of the possible suitable area for greening systems in a case study, and

TABLE 4 Possible available areas for greening systems in some case studies.

Case study	Roof cover	Current green roofs [ha]	Front and back yard green %	Possibility of green roofs [ha]	Ref.
Os. B. Śmiałego (Poland)	17.3%	—	5	44.4	Zwierzchowska et al. (2021)
Karl-Marx-Allee (Germany)	15.3%	—	5.4	46.3	
Berlin (Germany)	10,256 ha	400 (3.9%)	—	—	
Thessaloniki (Greek)	—		—	229 (16.7% of all buildings' roofs)	Theodoridou et al. (2017)
Braunschweig (Germany)	3%	—	—	300 (14% of all buildings' roofs)	Grunwald et al. (2017)
Paris	—	14.1 (0.21%)	—	—	Versini et al. (2020)
Amsterdam	—	10.86 (0.16%)	—	—	
Genova	—	65.3 (0.93%)	—	—	

the production yields based on the mentioned factors, could be applied to find out the potential of urban farming. Plenty of studies deal with using aerial imagery to extract features relevant to different purposes, such as urban ecosystems, heat islands, city management plants, and solar PV installation. (Zhao et al., 2015; Williams et al., 2016; Grunwald et al., 2017). Forster et al. used GIS and RS image processing for mapping urban agriculture (Buehler, 2009). Xiao et al. developed an automatic method for detecting rectangular flat roofs from DEM images (Xiao et al., 2010). Palmer et al. developed a GIS-based method for detecting suitable rooftop areas for PV installation. The used data included LiDAR (Light Detection and Ranging) and aerial photographs, and the results show the method's effectiveness (Palmer et al., 2018). In another study, Kang et al. developed a framework for classifying different urban land uses (apartment, office, church, garage, etc.). They combined Google images and Google Street View and developed a Street View benchmark dataset. By training Convolutional Neural Networks (CNNs), the framework could classify the type of buildings (Kang et al., 2018). Wu et al. developed a platform named "roofpedia" to monitor the current use of rooftops using satellite images. They used geospatial techniques and deep learning, and the method can determine the total area of solar panels and green roofs in a region to be used in urban management decisions (Wu and Biljecki, 2021).

2.4 Potential rooftop and garden agriculture in some european case studies

The potential rooftop and garden agriculture in some case studies within Europe is presented in Table 4. The roof cover percentages are from 3% to 24.8% of the city area, and possible areas for green roofs/urban farming, suitable for this purpose, correspond to about 14%–16.7% of the total roof area (Grunwald et al., 2017; Theodoridou et al., 2017). Moreover, around 5% of the city area is house yards that also could be suitable for green roof/urban farming (Grunwald et al., 2017).

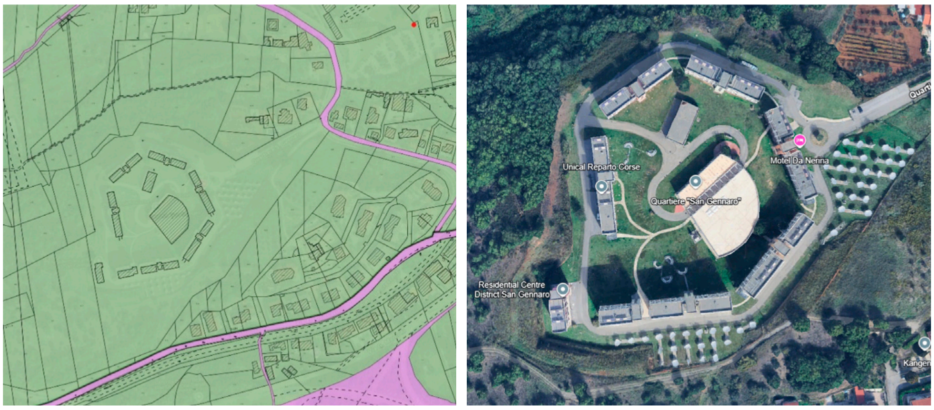
In addition, when evaluating the potential of urban rooftop agriculture, the geometry of the roof and the structural capacity of the building (load-bearing capacity, and structural safety) must also be considered, and generally flat roofs offer the most suitable conditions.

2.5 Case study definition

For case study analysis, a residential center at the University of Calabria named San Gennaro resident, with 184 students, has been selected, and the potential rooftop cultivation has been analyzed, Figure 3. The university is situated in the city of Rende, which has a Mediterranean climate.

The proposed decentralized rooftop and yard agriculture system integrates fog water harvesting, domestic greywater reuse, and container or substrate-based rooftop/balcony/yard cultivation of two multipurpose crops of maize and sunflower. Figure 2 illustrates the conceptual flowchart, and to ensure replicability and comparability with other WFE-Nexus studies, the following points need to be considered:

- Water Requirement has been calculated for a 100 m^2 cultivation area;
- The water requirement in the growing period for selected plants can be assumed according to Table 1;
- The crop yield (corn or maize) can be determined according to Section 1.1;
- Fog harvesting potential in the selected location can be calculated according to Table 2;
- Greywater characteristics are taken from values commonly reported in European residential buildings, as presented in Table 3;
- Greywater value can be estimated according to Section 2.2;
- The equivalent meat and oil yield for the selected crop can be estimated according to the data in Section 1.1;
- Soil salinity is assumed to be negligible due to the use of a rooftop substrate.



(a) (b)

FIGURE 3
Selected case study for investigation of the potential of rooftop cultivation.

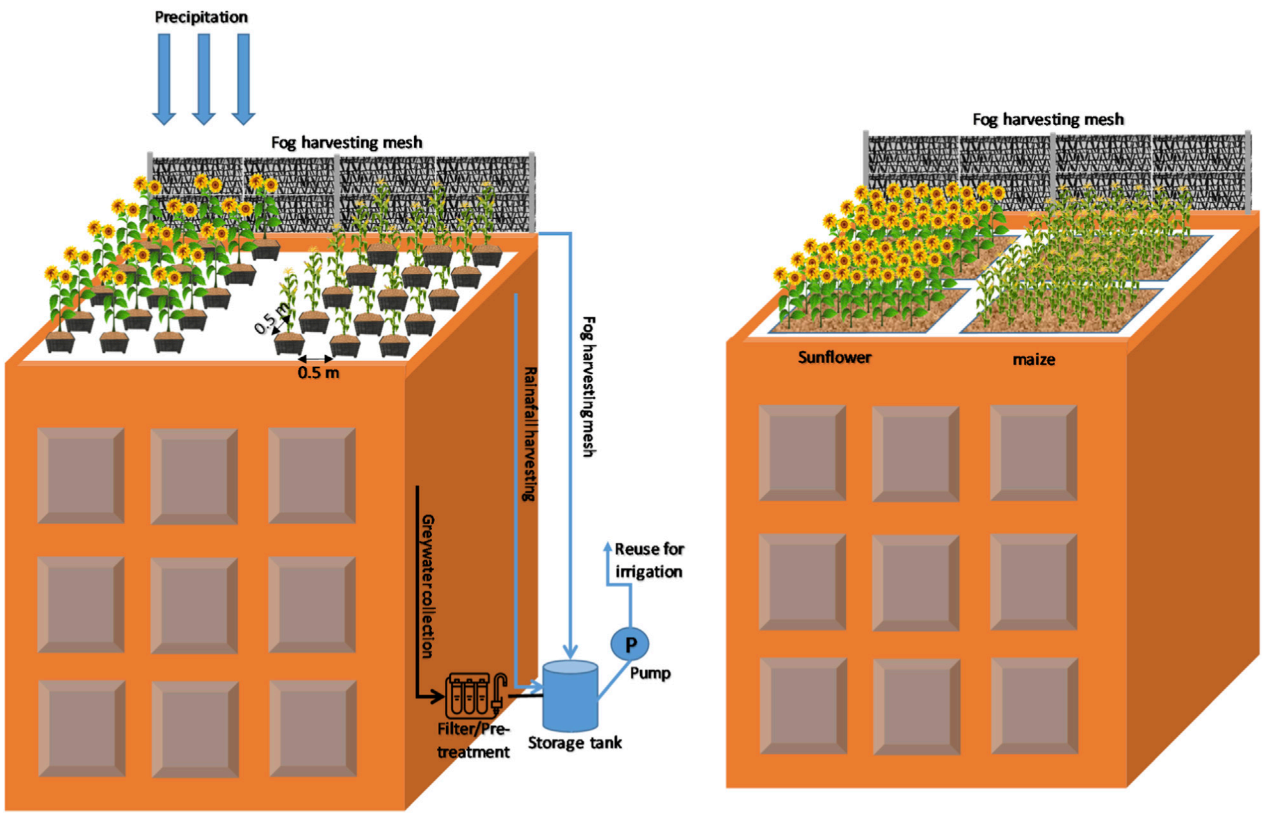


FIGURE 4
Schematic of rooftop cultivation/container gardens with fog water harvesting.

3 Results and discussion

3.1 Feasibility of rooftop, balcony, and yard cultivation in the urban environment

From what we pointed out in Section 1.1 and according to maize and sunflower root penetration lengths, it is possible to plant both maize and sunflower in an Extensive Green Roof (with a soil layer of more than around 20 cm) or in a container. Figure 4 presents two methods for planting maize and sunflower combined with fog harvesting mesh on the roof side wall. The fog harvesting mesh that can be installed on two sides of the roof can decrease the restrictions of rooftop cultivation in two ways. It can decrease the wind impact by

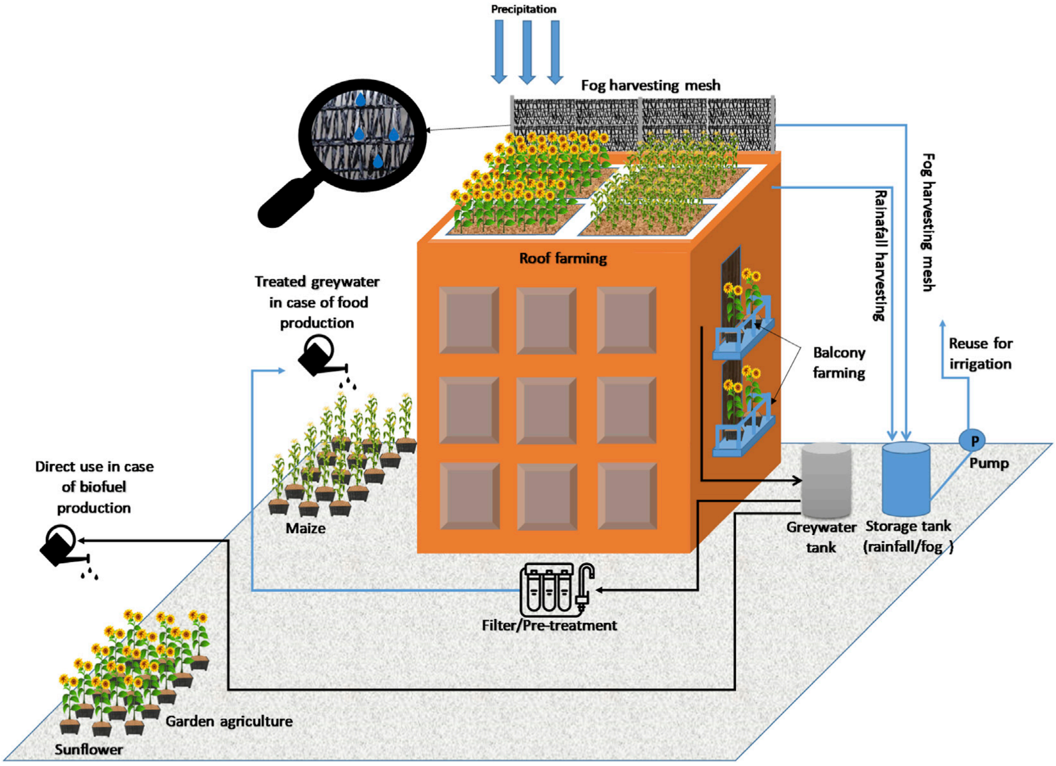


FIGURE 5
Schematic of urban farming (rooftop, balcony, and yard) with fog water harvesting and greywater.

creating shadows, reducing direct sunlight, and resulting in high-temperature impacts.

The height of the fog harvesting mesh and installation on one or more sides of a building would depend on the climate and water requirements. According to Table 2, in the Mediterranean climate during summer, the fog harvesting potential is between 1.6 and 4.6 L/m^2/day. Therefore, for a fog mesh area equal to 40 m^2 (length: 20 m × height: 2 m), the water harvesting in the whole summer would be around 5.9–17 m^3 (40 m^2 × 4.6 L/m^2/day × 92 days = 16.9 m^3).

Figure 5 shows the potential area for planting maize and sunflowers, including the rooftop, balcony, and yard. Specifically, balcony and yard cultivation can be a suitable choice if the severe windy conditions in a region do not allow rooftop cultivation. The system is a hybrid infrastructure (container gardens, rainwater harvesting, greywater, and atmospheric water harvesting), and the potential of urban farming could be analyzed as rooftop/yard/balcony agriculture for strategic plants (plants that can be used for both human/animal food and biofuel, such as maize). Moreover, the container gardens have another advantage: they can be distributed before the growing period and collected afterward to rotate the planting system. By a rotation planting system between winter variety and summer variety, optimal soil C budget and nitrogen practice could be improved, and decrease the use of fertilizer (Wang et al., 2015; Liang et al., 2020).

As can be seen in Figure 5, fog water harvesting can be used directly for the irrigation of plants. Due to the possible contamination hazard, greywater can be used directly if the final goal is biofuel production or after filtration/pre-treatment if the goal is food production.

3.2 Calculation of the rooftop/yard agriculture yield (food and energy) for the selected crops (maize and sunflower)

In Table 5, we display the annual yields for urban maize and sunflower, evaluated for a 100 m^2 area in Italy with a Mediterranean climate.

The comparisons of water requirement and fog harvestings/greywater in the example show that the greywater could be enough for total irrigation, while the value for fog harvesting is a maximum of 28% for sunflower and 34% for maize water requirements. The comparison favors maize over sunflower production. The main reasons are their use in food production, shorter growing periods, and higher yields.

With the same scheme, evaluating the production yield of both crops in different case studies and cities would be possible. To do this, the available area percentage and hectare (roof, yard, green roofs) can be derived from Table 4. The water requirement for maize and sunflower is shown in Table 1. The fog harvesting potential in different climates is shown in Table 2, and greywater is shown in Table 3. By comparing these data and considering the summer rainfall, one can determine the amount of water required for irrigation and the portion that could be obtained from fog harvesting and greywater.

TABLE 5 Calculation of annual yield (food and energy) for a 100 m^2 area (10 × 10) in Italy with a Mediterranean climate (growing period: 3 months during summer).

Crop	Water requirement[a] [m^3]	Annual yield[b] [kg]	Fog harvesting mesh in 2 sides of roof (20 m × 2 m)[c] [m^3]	Domestic greywater for a 3-floors building with 8 person[d] [m^3]	Equivalent meat[e] [kg]			Oil[f] [kg]	Equivalent biofuel[g] [liter]
					Beef	Pork	Chicken		
Maize	50–80	119.4	5.9–17	73–110	17	33	47	—	51
Sunflower	60–100	52.9			—	—	—	18.5	—

[a] According to Table 1. The water requirement of maize is about 500–800 mm in the total growing period, and for sunflower, 600–1,000 mm. Therefore, for a 100 m2 area, the water requirement for maize would be 50–80 m3, and for sunflowers, it would be 60–100 m3.

[b] According to Section 1.1, the corn yield in Italy is about 11.94 tons per hectare, which for 100 m2 would be equal to 119.4 kg, and for sunflower, the yield in central Italy is 5.29 tons per hectare, which for 100 m2 would be equal to 52.9 kg.

[c] According to Table 2: 40 m2 × 4.6 L/m2/day × 92 days = 16.9 m3, and 40 m2 × 1.6 L/m2/day × 92 days = 5.9 m3

[d] According to Section 2.2, greywater value is about 100–150 L/PE/day, which would be around 73–110 m3 for eight people during summer.

[e] According to the data in Section 1.1, the calculations have been made (25 kg of corn can produce about 7.7 kg of animal food (3.6 kg beef, 7 kg pork, 9.8 kg chicken).

[f] According to Section 1.1, the oil yield is about 35% of the seed weight (1,850 kg ha-1), which would be 18.5 kg in 100 m2.

[g] According to the data in Section 1.1, the calculation has been made (25 kg of corn can produce 10.6 L of ethanol).

FIGURE 6
Cadastral map of the selected area.

Fog water and domestic greywater can be stored using small-scale rooftop or ground-level tanks, depending on the available space and the building configuration. In the case of fog harvesting by mesh, the collected water can be drained by gravity into a storage tank under the mesh, while greywater can be routed from household outlets to a compact treatment and storage unit located on the balcony, rooftop, or building courtyard. Due to the continuous production of greywater in a building, its storage and reuse will not involve the installation of a huge tank and operational costs. The infrastructure can consist of a small tank (i.e., 1 m^3 for balconies or rooftops) equipped with a basic filtration or pre-treatment stage and a low-power pump for reuse.

3.3 Case study analysis

In this section, the potential of urban rooftop agriculture is analyzed using two methods. The first method, which is possible as a free tool for Italy, is to apply a cadastral map. The roof area of the selected building can be calculated according to the cadastral code of each building, Figure 6, and the total area of roofs is equal to 4,879 m^2.

In the second method, we used image processing in MATLAB R2024b. In this regard, a code has been developed according to the roof colors provided in Appendix A. The provided code, which creates a logical mask based on RGB thresholds, can be updated by a

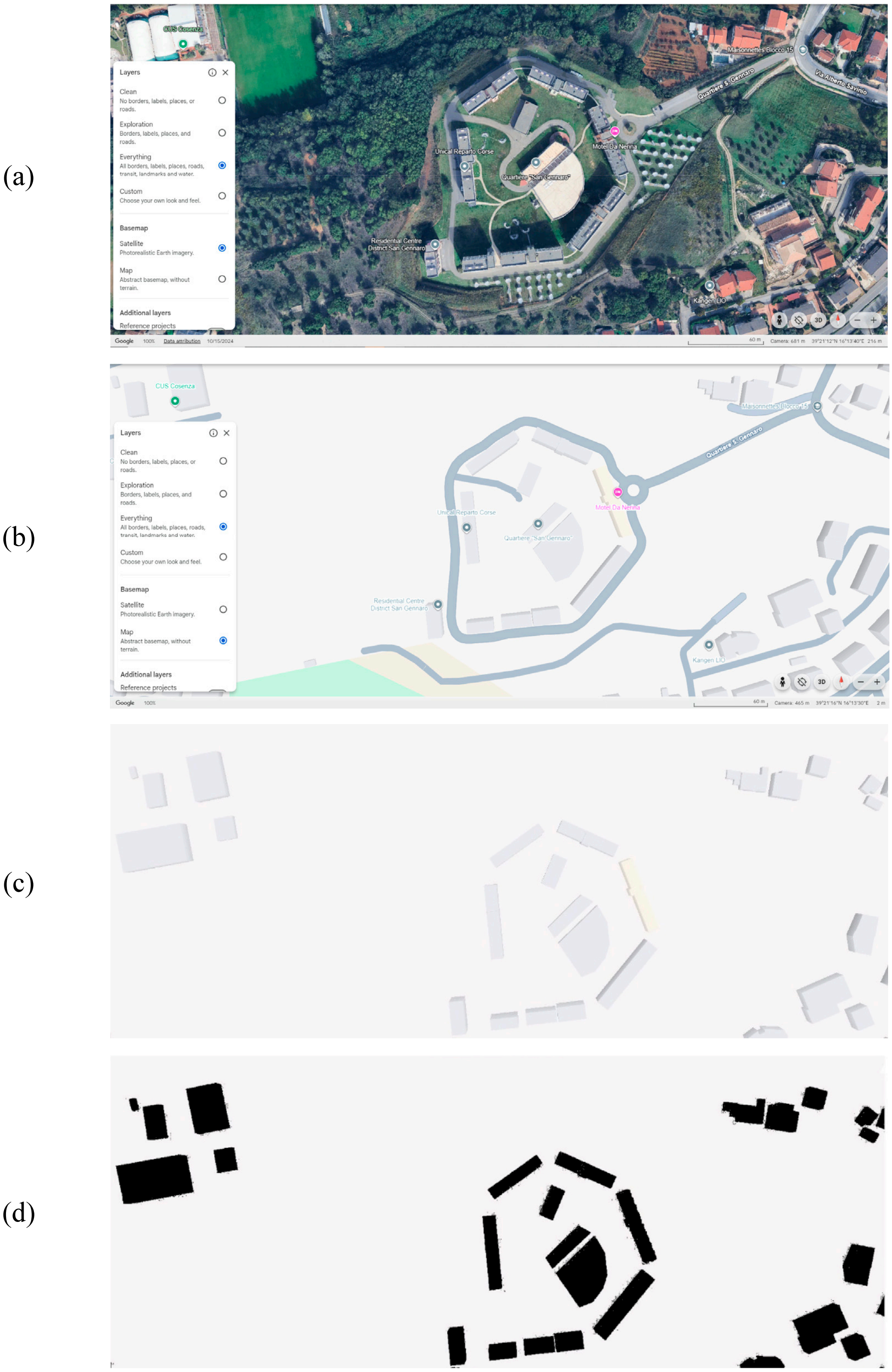


FIGURE 7
Cadastral map of the selected area: **(a)** Satellite image in Google Earth; **(b)** Map with details in Google Earth; **(c)** Clean map; **(d)** masked image with rooftops in black in MATLAB R2024b.

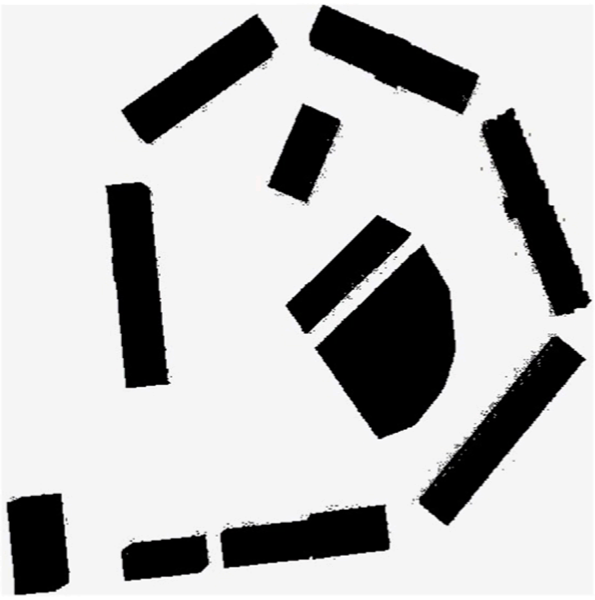


FIGURE 8
Masked image with rooftops in black using MATLAB R2024b.

user for new regions and according to the area's color that needs to be determined. The procedures of image processing in these methods and the final result are presented in Figure 7.

The final result for the selected area is shown in Figure 8, showing a total roof area of about 5,097 m^2, an error of about 4% compared with the cadastral area.

The annual yields for rooftop cultivation of maize and sunflower are presented in Table 6.

While the value of the equivalent biofuel or meat can be calculated according to the local market in the case study, the economic benefit is not limited to the production amounts. The cost-benefit analysis of urban rooftop/yard biofuel or agricultural productions is a complicated subject that does not simply contain measurement variables. The cost of green roofs includes initial and maintenance costs. From the total costs, initial costs contribute between 78% and 86%, and maintenance costs between 12% and 22% (Hekrle et al., 2023). The green roof construction cost in 2016 was approximately 100 USD (Nurmi et al., 2016), and decreased to 120 USD in 2019 (Shin and Kim, 2019). In contrast, the benefits of agricultural roofs are vast, mainly including runoff regulation, energy savings on heating and cooling, interior noise reduction, air quality improvement, CO_2 reduction, aesthetic improvement, and an increase in insulation lifespan (Hekrle et al., 2023).

The benefits of agricultural roofs are most obvious during the growing season, when vegetation contributes to evapotranspiration cooling, shading, carbon absorption, and food or biofuel production. However, similar to conventional green roofs, agricultural roofs also provide several long-term environmental advantages.

Outside the crop season, the presence of substrate/drainage layer, and residual root structures improves thermal insulation in winter, moderates indoor temperatures, and contributes to stormwater retention. Therefore, although the magnitude of benefits varies with plant activity, agricultural roofs share many of the hydrological, thermal, and environmental services offered by green roofs while additionally supporting urban food and energy production during the crop growing season.

The economic value of rooftop or container agriculture does not come from crop revenue alone. The system provides additional benefits such as stormwater mitigation, reduced heat island effects, lower building energy consumption, improved insulation lifespan, and increased water-use efficiency. When these co-benefits are considered, the suggested systems can be economically feasible, even when direct agricultural yields are modest.

In addition, the benefits of biofuels are not just based on the value of production but also depend on the impact category considered, such as CO_2 reduction, a renewable and sustainable energy source, reducing reliance on fossil fuels, promoting a cleaner environment, economic advantages, and creating new jobs in the agricultural sector. In this way, the cost-benefit analyses (CBA) are challenging to apply to biofuels and bio-based products because of the wide range of environmental impacts they should comprehend (Gabrielle et al., 2016).

3.4 Comparative advantages, feasibility, and scalability of the proposed system

The analysis demonstrates that the combined use of fog harvesting, domestic greywater reuse, and rooftop/container agriculture creates a decentralized Water–Food–Energy (WFE) solution that may overcome several limitations of conventional approaches.

The main advantages are as below:

- Conventional green roofs can support vegetation for environmental benefits, but do not produce meaningful quantities of food or biofuels;

TABLE 6 Calculation of annual yield (food and energy) for the selected rooftop area (4,879 m^2).

Crop	Water requirement [m^3]	Annual yield [ton]	Equivalent meat [kg]			Oil [kg]	Equivalent biofuel [liter]
			Beef	Pork	Chicken		
Maize	2,440–3,903	5.8	835	1,624	2,274	—	2,459
Sunflower	2,927–4,879	2.6	—	—	—	910	—

- Rainwater harvesting systems provide limited irrigation; however, in the Mediterranean climate, precipitation in summer is near zero;
- Centralized greywater treatment systems require high capital investment, but the presented method, based on the multipurpose crops, enables agricultural productivity with minimum water-energy inputs.

The quantitative analysis approved that the greywater produced by an eight-person residential building (73–110 m^3 per summer) can fully satisfy the irrigation demand of maize and sunflower grown on a 100 m^2 roof, while fog harvesting can contribute up to 34% of maize and 28% of sunflower water requirements. Therefore, it confirms the feasibility of crop growth in the presented system independently of the urban potable water network.

The presented approach is scalable from individual buildings to residential districts under the following conditions:

- Verification of rooftop structural capacity;
- Implementation of greywater separation and treatment at the household level;
- Application of modular container systems to reduce load;
- Appropriate installation of the fog harvesting system (orientation and dimension).

Finally, for broad adoption, policy supports including incentives for greywater-reuse infrastructure, guidelines for rooftop agricultural activities, and integration of fog harvesting and urban agriculture into climate-adaptation plans could be suitable to strengthen food and energy resilience within the urban environment.

4 Conclusion

In this study, the advantages of greening systems in an urban environment for decreasing climate change impacts, such as stormwater management and wastewater treatment, besides the importance of simultaneous consideration of food and energy security, have been analyzed. The analysis of the greening systems in urban environments shows several advantages. Moreover, the analysis of urban farming showed food security benefits. In addition, analysis of the food vulnerability showed that the strategic grain in each region could be different, and two multipurpose grains of maize and sunflower could be counted as strategic crops since, besides human and animal food, the role of these grains in biofuel production makes them a suitable choice for future consideration. Their planting requirements make them suitable for planting in rooftops or containers to be put in house yards, balconies, and rooftops, or as green roofs.

Furthermore, the fog harvesting potential in different climates and the feasibility of using greywater for irrigation have been investigated, showing the possibility of using both water sources for irrigation. Besides, domestic greywater quality and quantity analysis show advantages and ease of application for urban farming. Green areas such as green roofs could also be used for wastewater treatment; in our case, this adds to the first goal of biofuel production.

Finally, the feasibility analysis of urban farming in rooftop and container agriculture using fog and greywater has been explored, and the advantages of the proposed system for food and biofuels by maize and sunflower are examined in a Mediterranean climate. Water quality analysis determined that fog water harvesting can be used directly for the irrigation of plants. However, in the case of greywater, due to the possible organic contamination hazard, it can be used directly if the final goal is biofuel production or after filtration/pre-treatment if the goal is food production. The same management can be done for the cases where an environmental pollution hazard exists.

Additionally, comparing water requirement and fog harvestings/greywater shows that the greywater could be enough for the total irrigation requirement for both crops, while the value for fog harvesting is a maximum of 28% for sunflower and 34% for maize water requirements during the growing period (summer). In conclusion, the suggested system could be a suitable tool to mitigate some impacts of climate change, besides decreasing global food and energy security vulnerability using urban farming of strategic multipurpose plants for food and biofuel.

The presented method offers several comparative advantages over existing approaches, including resource efficiency by reuse of greywater, decentralization for both water supply and crop production, productivity by multifunctionality of urban agricultural spaces, and environmental benefits.

5 Recommendations for future studies

This study confirms the feasibility of the proposal. However, future studies can analyze the total possible production yield through GIS and image raster with a new case study analysis in different types of climates. In addition, since the wind and high temperature can restrict rooftop cultivation, the impacts can be simulated using CFD models, so it is suggested for future investigations. Moreover, the development of water balance models for selected plants according to water requirements, rainwater harvesting, direct precipitation, fog harvesting, and greywater is suggested for future studies. It has to be stressed that the role of collection points is crucial and can be analyzed and optimized by AI. This, as well as cost-benefit analysis, may be an object of future investigation. Finally, several highly efficient irrigation methods, such as sub-surface and drip irrigation, can reduce water consumption and are useful for decreasing water consumption in regions with scarce water resources. However, in this paper, the primary focus is on developing and assessing a new hypothesis for rooftop and yard cultivations; therefore, analysis of highly efficient irrigation methods can be considered in subsequent studies.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

BP: Conceptualization, Data curation, Investigation, Methodology, Writing – original draft, Writing – review and editing, Software, Project administration, Visualization, Resources, Validation, Formal Analysis. SP: Data curation, Investigation, Resources, Writing – review and editing, Methodology, Formal Analysis, Writing – original draft. HJ: Formal Analysis, Writing – original draft, Software, Visualization, Data curation, Methodology, Writing – review and editing, Validation, Investigation. PP: Writing – review and editing, Supervision, Writing – original draft, Funding acquisition, Project administration. MT: Formal Analysis, Writing – original draft, Methodology, Data curation, Resources, Writing – review and editing, Investigation.

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