



Brewing sustainability: unveiling the potential of coffee ground as green roof media

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Abstract

The rapid depletion of the world's natural resources and the growing concerns about sustainability underscore the importance of environmentally friendly solutions more than ever. One such solution is green roofs, which offer numerous ecological benefits, particularly in urban areas, such as creating natural habitats, enhancing energy efficiency, and improving air quality. Recently, as access to safe food has become more challenging and economic conditions have not been that stable all over the world, the importance of green roofs has been increasing in urban areas where it is difficult to create green surfaces for many reasons, especially profit. In this context, using coffee grounds as a green roof plant growth medium and a waste product holds significant potential for waste management and sustainable agriculture. With the influence of previous researches, coffee grounds are supposed to support plant growth due to their high organic matter content and nutrient values. This study aims to support the environmental benefits and the contribution of this approach to sustainable urbanization by examining the effects of using coffee grounds on green roofs on plant development. This study assessed the growth of *Fragaria ananassa* and *Sedum spurium* in growing media comprising 20% and 50% coffee ground. In *F. ananassa* a reduction of 9.25–13.58% in plant height, 18.71–23.93% in the number of stolons, 1.36–40.34% in chlorophyll content, and 10.49–13.78% in plant diameter was noted in the medium containing 20% coffee ground, while an increase of 39.20–45.81% in the fruit count and 4.79–9.42% in root collar diameter was recorded in the medium devoid of coffee ground. In *S. spurium*, a 22.76% reduction in plant height, a 13.11% decline in chlorophyll content, a 25.26% decrease in plant diameter, and a 4.40% increase in root collar diameter were recorded in the medium containing 20% coffee ground. A medium including 50% coffee ground resulted in a 42.36% reduction in plant height, a 12.44% reduction in chlorophyll content, a 46.13% reduction in plant diameter, and a 19.10% reduction in root collar diameter. The results indicate that the impact of coffee ground on plant growth varies based on the ratio, necessitating the establishment of suitable application ratios.

Keywords Coffee ground · *Fragaria ananassa* · *Sedum spurium* · Roof garden · Drought

Introduction

Urban areas have been experiencing sustainability problems, especially in the last century, due to climate change, increasing population and deteriorating quality of natural areas close to them all over the world. While heat island effects, difficulties in stormwater management and vegetation and habitat loss are the major problems, green roofs could solve these problems, although commercially available green roof substrates also present certain challenges (Haeldermans et al. 2023). In spite of the fact that green roofs have emerged as a move to contribute to sustainability, problems like the extra weight they bring to buildings, the use of non-sustainable materials as a growing medium,

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problems in plant root development and the variability of irrigation needs have always led to researches for growing media on green roofs. The use of organic waste as green roofs growing medium as a solution to these basic problems is a result of these searches. Although use of waste material for green roofs is relatively new phenomena, it is possible to see these materials for basically two different purposes: As drainage layer (Cascone and Gagliano 2022; Kazemi et al. 2021; Romali et al. 2023) and substrate (Eksi et al. 2020; Fan et al. 2020; Xue and Farrell 2020).

Waste generation is a natural consequence of production and consumption activities. Solid, liquid, and gaseous wastes are inevitably produced as residues in the production process or as substances that can integrate into nature after consumption. Therefore, the more production and consumption, the more waste generated (Demirci 2024). Effective waste management strategies in cities enhance both ecological sustainability and the quality of life for urban populations. As waste materials become important problems that countries all over the world have to deal with, it is inevitable that new developing technologies and approaches will be adapted to this issue. The application of artificial intelligence in waste-to-energy, smart bins, waste-sorting robots, waste generation models, waste monitoring and tracking, plastic pyrolysis, distinguishing fossil and modern materials, logistics, disposal, illegal dumping, resource recovery, smart cities, process efficiency, cost savings, and improving public health seeks to offset the frightening growth of the waste problem (Fang et al. 2023).

Recycling efforts and the need for reuse, coupled with increasing environmental awareness, have encouraged using compost organic biomass in agricultural practices. As a result, alternative growing media have begun to be utilized (Najafi 2014). This trend has led to the investigation of the usability of even marginal wastes such as sewage sludge in the growing medium, owing to the porous inorganic materials, high porosity, surface area, passivation capacity, high recycling potential and potting soil components they contain (Dede et al. 2023). Studies on alternative growing media have used various materials such as coconut husk, tea waste, composted bark, corn stalks, sawdust, grape pomace, nutshells, tobacco waste, and spent mushroom compost. Recycling waste in food products is particularly important for utilizing organic matter (Najafi 2014; Vidyasagaran et al. 2014). Organic materials are repurposed for alternative uses by converting them into different materials or substances through their initial purposes (Öktem 2016).

In many ecological environments, mainly green roofs, the soil has a high bulk density and significantly increases mass when watered, substantially raising static project and application costs (Yalcinalp et al. 2017). Reducing this load is crucial. Thus, various methods are used to lighten the green roof

medium, constituting a major part of the roof load. However, while the suitability of recycled waste as a green roof substrate raw material is assessed based on factors like nutrient content, water retention capability, pH level, salinity range, porosity and stability (Kader et al. 2024) and all these characteristics can affect the depth of the medium, especially climate and plant species can also be important variables to determine the depth (Leotta et al. 2023). Therefore, the depth of the substrate on green roofs should be determined by considering the load to be placed on the structure and the requirements of the artificial habitat to be created. Although many scientific studies are being carried out to popularize green roofs and increase the benefits they will provide for the world, the need for researches in this field is still high to contribute to sustainability by ensuring the use of waste materials, to facilitate access to green roofs by reducing costs and to get rid of the burden spent on storing waste materials.

According to the literature, sustainability is evaluated based on whether the consumed natural resource value has formed in the last 100 years. Soil formation takes thousands of years; thus, by this definition, soil is not a sustainable resource. Due to the difficulty of its formation and the long time it takes, soil is a natural resource that must be used carefully (Demirci 2024; Yeni 2014). Considering the sustainability value of coffee, this study's primary material is its sustainable use. The cultivation and preparation of coffee for consumption do not take hundreds of years. However, coffee farming is often criticized for ecological reasons. The primary concern here is the utilization of waste (Demirci 2024).

In the study, pot trials were established by mixing coffee grounds with soil in varying doses (100% soil / 20% coffee-80% soil / 50% coffee-50% soil), and the growth of *S. spurium* and *F. ananassa* species was observed in these environments. Parameters such as plant height, fruit number, stolon number, chlorophyll value, plant diameter, growth medium EC value, growth medium temperature, and plant root collar diameter were recorded for the plants monitored during the vegetation period.

The research found that in *S. spurium* 'Atropurpureum,' growth decreased as coffee in the growing medium increased. In contrast, in *F. ananassa*, the number of fruits increased, and the maturation period shortened as the coffee amount increased.

The research was initiated by focusing on the question of whether coffee ground can be used to lighten, economize and make green roofs more sustainable.

Main aims of this study are:

- To prevent the ground left over from coffee, which is consumed widely around the world, from becoming a burden on the environment as waste.

- Supporting the search for lightweight and sustainable habitat for green roofs.
- To question the potential of coffee ground for edible green roofs, in line with the possibility of using green roofs in the near future for access to safe food,
- Developing a reflex to reduce the use of unsustainable materials in green roofs,
- Taking a step towards using a natural resource such as soil, which takes a long time to form, as limited as possible on green roofs to protect the environment.

Plus, it can be said that the unique aspect of this study is the monitoring and trying to explain the developmental characteristics of two different plant species in coffee-soil mixtures at different ratios in the green roof simulation created. Thus, it will be possible, on the one hand, to obtain results that will shed light on future studies on sustainability in green roofs, and on the other hand, to create motivation for transforming a waste material into an ecologically and economically sustainable resource value to make the green roofs cheaper and more common all over the world.

The annual coffee grounds production is estimated to be 9.4 million tons globally. The environmental effects of such a significant amount of coffee production are inevitable. Coffee production is basically done in two ways: the dry technique, which is a traditional and environmentally friendly method, and the wet technique, which is an industrial method that requires the use of a large amount of water during production (Genanaw et al. 2021). Although serious efforts are made to purify this wastewater as much as possible, it directly and indirectly affects water resources due to the large amount and the size of the geography where it is applied. These wastes pose environmental problems for coffee-producing countries and affect rivers and lakes near coffee processing areas (Carmen et al. 2020; El Achaby et al. 2019; Roussos et al. 1995). The coffee producing process produces significant liquid waste, which is usually directed into adjacent water bodies or utilised for irrigation. Despite significant attempts to treat this wastewater thoroughly, it impacts water resources both directly and indirectly due to its substantial volume and the extensive geographical area over which it is distributed. These wastes present environmental challenges for coffee-producing nations and impact rivers and lakes adjacent to coffee processing regions (Coelho et al. 2020; Lee et al. 2023; Stufano et al. 2022; Thriveni et al. 2017).

Using organic waste in growing media is considered one of the best alternatives to improve soil organic content. Consequently, composting, the process of converting organic waste into fertilizers or additives, is gaining increasing importance (Demirci 2024; Yaman 2012). Coffee grounds have been used to improve and develop soils through

composting methods, mycorrhizal inoculation, and phytoremediation (Horgan et al. 2023; Pagán-Roig et al. 2016; Wasilkowski et al. 2017). This has resulted in improved plant growth, production, biomass, and polymerization, as well as overall improvements in soil quality and fertility (Betancourt et al. 2016; Cervantes Beyra et al. 2015; Senthilkumar et al. 2015). Furthermore, it has been reported to enhance moisture, soil pH, and humification index and increase both macros (N, P, K, Ca, Mg) and micronutrient elements (Fe, Zn, Cu, Mg) (Campos Mota and Flores Sánchez 2018; Muñoz et al. 2015).

Materials & method

The present study aimed to repurpose coffee grounds by mixing them, as a source of organic matter, with soil in specific ratios to create alternative growing mediums for plants. In studies on green roofs, having the test site on a real roof can enable roof conditions to be simulated more realistically. However, in many scientific studies, it is also possible to see green roof test areas created with containers for ease of intervention and monitoring (Desouki et al. 2024; Gagliano and Cascone 2024; Paraskevopoulou et al. 2023; van der Kolk et al. 2023). This study also chose such a method for green roof simulation.

Study area

The study area chosen was the plant cultivation area on the southern slope of the Landscape Architecture Department Building at Karadeniz Technical University (40°59'27.02"N, 39°46'30.80"E) (Fig. 1). The city covers an area of approximately 4,685 km² and has a population of about 758,237 inhabitants, making it the second-largest principal city in the region (Anonymous 2024). The town is within the A8 grid system created by Davis (1965); Davis et al. (1988), with an annual mean rainfall of about 828,9 mm and a mean temperature of about 14.8 °C (MGM, 2025). The monthly mean temperature ranges from 7.3 °C in January to between 13 and 23.1 °C in August (Yalçinalp et al. 2019; Yalcinalp and Meral 2017; Yalçinalp et al. 2017; Yalçinalp and Meral 2019).

Experimental setup

Different growth media were distributed in equal volumes to 99 pots, 33 for each group, and the pots were made ready for planting. Since the study measured the reactions of two different plant species, *S. spurium* and *F. ananassa*, to growth media prepared with coffee grounds, the experiment was conducted in 198 pots.



Fig. 1 Study Area

In the study, pot trials were established by mixing coffee grounds with soil in varying doses (100% soil – 20% coffee; 80% soil – 50% coffee; 50% soil) and the growth of *S. spurium* and *F. ananassa* species was observed in these environments. Coffee ground typically possesses an acidic composition. The pH level of coffee ground was determined to range from 4.5 to 6. This amount was anticipated to generate an adverse environment for plant growth. It was also considered that, due to its density, the substance may restrict the roots' oxygen intake by diminishing air gaps, and the dissolved salts and caffeine present will adversely impact root development and plant health. Consequently, planting was not conducted using 100% coffee ground.

Sedum species are commonly used worldwide in extensive green roof applications (Ekşi and Uzun 2016). This study used *S. spurium* 'Atropurpureum,' one of the most frequently used *Sedum* species on green roofs. The drought tolerance of *Sedum* species has been proven in various academic studies. There are many scientific studies conducted to reveal the importance of the use of the *Sedum* genus in different areas, especially emphasizing drought tolerance (Cotoz et al. 2023; Desouki et al. 2024; Ji et al. 2024). Specifically, it has been determined that *S. spurium* can survive without water for up to 88 days (Getter and Rowe 2008). For these reasons, *S. spurium* 'Atropurpureum' was selected as the first plant for the experiment. *F. ananassa* is known for its nutritional value, the wide range of regions where it can grow worldwide, and ease of production. However, under

drought stress, the growth and productivity of the plants can be significantly affected (Sammarco et al. 2023; Yenni et al. 2022). Nevertheless, such studies provide an essential foundation for understanding the responses of *F. ananassa* plants to drought stress and enhancing their resilience in future agricultural practices (Emam and Mohamed 2020). Studies on the positive impact of the pollinator relationship of *F. ananassa* on urban ecology and strawberry fruit productivity (Atmowidi et al. 2022) are also evidence that strawberries could be an ideal alternative for green roofs. Strawberry is a plant that is very suitable for cultivation in urban areas thanks to its characteristics and whose contribution to agricultural fruit production is expected to be much greater in the near future (Kouloumprouka Zacharaki et al. 2024). Additionally, overcoming cultural barriers to green roofs, as highlighted in previous research by the research team, could significantly benefit from obtaining an agricultural product.

The research, as in many previous studies, was carried out by providing a method that simulates the rooftop on the ground due to the different advantages it provides. The containers used imitate extensive green roofs with the depth of substrate they provide. The ease of monitoring and intervention due to the experiences gained from previous scientific research (Yalcinalp et al. 2017; Yalçinalp et al. 2019) has made this method very advantageous.

Fig. 2 Variations in plant characteristics from the date of planting (**A**-March) to the date of the final measurement (**B**-September)



Fig. 3 A wire mesh fence was used to protect the experimental setup

Following the relocation of the containers to the experimental area, the plants were planted, and measurements commenced (Figure 2)

Plantings occurred during the first week of March 2022, and the specified parameters were measured monthly from April to September.

To ensure the reliability of the parameter measurements and to protect the experimental area from wildlife and human interference, a wire mesh fence with a 15 × 15 mm mesh size was installed (Fig. 3).

Since pollination is an important element in strawberry production, the pore size of the fence used to surround the field was chosen as large as possible, such as 20 mm. When selecting the mesh material, it was essential to choose one that would not obstruct rainfall and sunlight or cast a shadow on the plants, ensuring they were not deprived of their natural environment.

Plant growth measurements and soil analyses

To observe plant growth, measurements were conducted for plant height, plant diameter, plant collar diameter, chlorophyll values (SPAD), soil temperature, and soil pH throughout the vegetation period (April–September) for the two selected species. Additionally, the number of fruits in *F. ananassa* was recorded to assess fruit yield in various growing environments (Table 1).

Table 1 Methods to measure plant growth parameters

Parameter	Unit	Method
Plant height	cm	On-site measurement with strip meter
Plant diameter	cm	On-site measurement with digital caliper
Plant root collar diameter	mm	On-site measurement with digital caliper
Chlorophyll values	cci	On-site measurement with chlorophyll meter
Soil Temperature	°C	On-site measurement with digital thermometer
Fruit yield	pieces	On-site observation

Table 2 Methods and reference values used in measurements and analyses

Analyses Parameters and Methods	Very Low	Low	Moderate	High	Very High	References
Total N, % (Kjeldahl)	<0.045	0.045–0.09	0.09–0.17	0.17–0.32	>0.32	(FAO, 1990)
Av. P, mg kg⁻¹ , Alkaline Soil, (Olsen et al.)	<2.5	2.5–6.0	6.0–12.0	>12.0	-	(Ülgen and Ateşalp, 1972)
Organic Substance, % (Walkley-Black)	<1	1–2	2–3	>3	-	(Özkan et al., 2020)
pH , Measurement in the saturation extract	Acidic <6.0	Mildly Acidic 6.0–6.5	Neutral 6.5–7.5	Mildly Alkaline 7.5–8.5	Alkaline >8.5	(Özkan et al., 2020)

The EC (Electrical conductivity), pH, OM (organic matter), T.N. (total nitrogen), and available P (phosphorus) analyses were done in media from different mixtures (Table 2). Plants absorb phosphorus from their growth media as primary orthophosphate ion (H_2PO_4) and secondary orthophosphate ion (HPO_4). These ions are referred to as accessible phosphorus (Özkan and Demir 2023; Taş and Demir 2022).

Statistical analyses

The statistical analyses were conducted using SPSS Statistics 26 software. A One-Way ANOVA test was employed to assess whether varying amounts of coffee grounds in growing environments lead to differences among the selected parameters. Correlation analysis was also performed to investigate relationships between growing environments and the selected plant parameters (Yalçınalp et al. 2023).

Results and discussion

Plant growth environment

When examining growth environments created with coffee grounds at varying doses, notable distinctions were observed among groups concerning pH. Significant differences emerged between pure coffee grounds and pure soil groups regarding organic matter content, yet no significant variations were observed among experimental environments formed by blending these two media. Similar findings were noted for Total N levels in the growth environments. Concerning P ratios in these settings, while no significant differences were found among the established growth environments, significant variations were noted among pure soil, pure coffee grounds, and growth environments (Table 3). The letters presented in the table denote the LSD (Least Significant Difference) outcome. These letters denote the

Table 3 Growth environment analyses

Coffee %	100	50	20	0
pH	5.663a	6.763b	7.193c	7.710d
OM	14.156b	12.653ab	11.816a	11.353a
Total N	0.706b	0.633ab	0.593a	0.570a
P	0.235c	0.264b	0.270b	229.670a

presence of statistically significant differences among the groups.

Sedum spurium

The effect of coffee additions on environments was assessed using One-Way ANOVA analysis. Analyses conducted for *S. spurium* revealed no significant differences between chlorophyll count and soil temperature parameters. However, significant variations were found among environments in other groups regarding their effects on parameters (Table 4).

Analysis of the data for *Sedum* plants reveals a considerable reduction in plant height as the percentage of coffee ground increases. This suggests that a high amount of coffee inhibits plant growth. Chlorophyll concentrations were elevated at 0% coffee content. This outcome suggests that the application of coffee may influence the photosynthetic capability of plants. A notable reduction in plant diameter was noticed with rising coffee content. Moreover, root development was enhanced in the 20% coffee treatment, whereas increased concentrations resulted in a reduction in root diameter (Fig. 4).

This study utilised Pearson correlation analysis to evaluate the correlations among several factors (Table 4). The statistical analysis revealed a substantial negative correlation between coffee ratio and plant height ($r = -0.677, p < 0.01$). This outcome suggests that a higher coffee ratio reduces plant height. A robust and affirmative correlation was noted between plant diameter and plant height ($r = 0.799, p < 0.01$). This signifies that an increase in plant height correlates with an increase in plant diameter. A significant and weak connection was identified between chlorophyll concentration and plant diameter ($r = 0.123, p < 0.05$). This outcome signifies that an augmentation in chlorophyll content results in a marginal rise in plant diameter. A substantial negative correlation existed between coffee concentration and root collar

Table 4 One-way ANOVA analysis results for *S. spurium*

Coffee (%)	0	20	50
Plant height	13.477a	10.386b	7.750c
Chlorophyll	28.773a	25.000a	25.193a
Plant diameter	33.431c	24.984c	18.007a
EC	.0865a	1.393b	1.448b
Temperature	23.909a	24.615a	24.832a
Root collar	3.769b	3.935b	3.049a

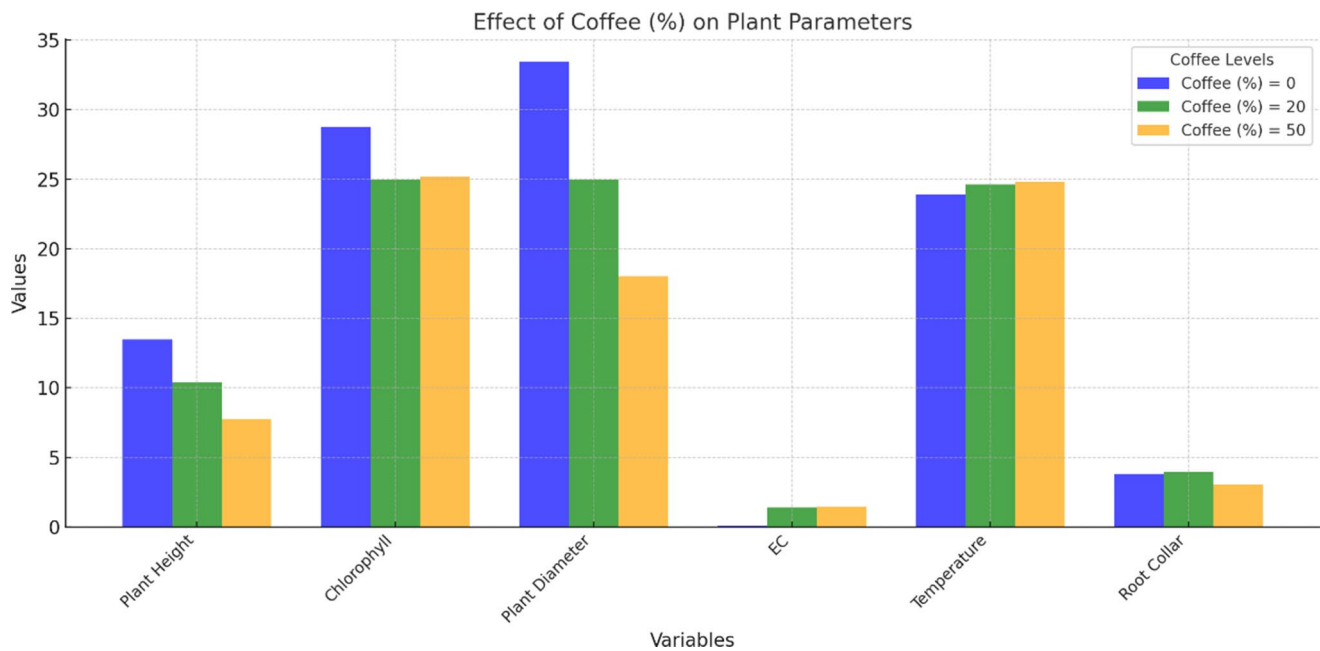


Fig. 4 Effect of coffee (%) and *S. spurium* plant parameters

diameter ($r = -0.193$, $p < 0.01$). This signifies that the root collar diameter diminishes with an increase in coffee concentration. A substantial negative correlation was identified between temperature and root collar diameter ($r = -0.103$, $p < 0.05$). This outcome signifies that the rise in temperature adversely impacts root collar diameter (Table 5; Fig. 5).

This study found that the acidic chemicals and elevated caffeine levels in coffee ground adversely impacted *Sedum* growth. Furthermore, an increase in coffee concentration within the nutritional medium may lead to reduced plant height because to enhanced water retention and restricted water accessibility (Guo et al. 2021). The results revealed a 22.76% reduction in plant height, a 13.11% decline in chlorophyll count, a 25.26% decrease in plant diameter, and a 4.40% increase in root collar diameter for *S. spurium* in the growing media containing 20% coffee ground compared to the media devoid of coffee ground. A growing media containing 50% coffee ground exhibited a 42.36% reduction in plant height, a 12.44% decline in chlorophyll count, a 46.13% decrease in plant diameter, and a 19.10% reduction in root collar diameter when compared to a medium devoid of coffee ground.

Fragaria ananassa

A one-way ANOVA test was conducted to examine the effects of the additional coffee amounts on the parameters. The analyses on *F. ananassa* revealed no significant relationships between groups regarding plant diameter and soil temperature. However, significant relationships were found

between the effects of the environments on the parameters in the remaining groups (Table 6).

Analysis of the data gathered for the *F. ananassa* plant revealed that an increase in coffee rate resulted in a decline across the entire plant. The quantity of fruits harvested from the strawberry plants rose in conjunction with the growth in coffee quantity. The quantity of stolons diminished as the coffee % increased. The reduction became more evident as the coffee content increased. A notable reduction in chlorophyll concentration was found with the increasing amount of coffee. The diameter of the plant exhibited no significant variation with the increase in coffee content. Root development was optimised with the treatment containing 20% coffee (Fig. 6).

The correlation study offered a detailed examination of the links between coffee % and several plant factors. An increase in coffee % correlates with a rise in fruit quantity ($r = 0.112$, $p < 0.05$), plant height ($r = 0.209$, $p < 0.01$), and chlorophyll concentrations ($r = 0.126$, $p < 0.05$), while also positively influencing electrical conductivity (EC) ($r = 0.176$, $p < 0.01$). Nonetheless, the percentage of coffee exerted no significant influence on temperature. A notable rise in stolon count ($r = 0.675$, $p < 0.01$), plant diameter ($r = 0.715$, $p < 0.01$), and soil conductivity ($r = 0.805$, $p < 0.01$) was seen with time. Nonetheless, temperature ($r = -0.543$, $p < 0.01$) exhibited a tendency to decline as the month advanced. The quantity of fruit exhibited a positive correlation with time ($r = 0.384$, $p < 0.01$) and electrical conductivity ($r = 0.309$, $p < 0.01$), whereas the number of stolons was negatively linked with the quantity of fruit ($r = -0.351$, $p < 0.01$). Chlorophyll concentrations exhibited a positive

Table 5 Inter-parametric correlation analysis

		Month	Coffee (%)	Plant Height	Chlorophyll	Plant Diameter	EC	Temperature	Root Collar Diameter
Month	Pearson Correlation	1							
	Sig. (2-tailed)								
	N	396							
Coffee Ground (%)	Pearson Correlation	0.000	1						
	Sig. (2-tailed)	1.000							
	N	396	396						
Plant Height	Pearson Correlation	0.307**	−0.677**	1					
	Sig. (2-tailed)	0.000	0.000						
	N	396	396	396					
Chlorophyll	Pearson Correlation	0.096	−0.090	0.090	1				
	Sig. (2-tailed)	0.056	0.073	0.073					
	N	396	396	396	396				
Plant Diameter	Pearson Correlation	0.496**	−0.640**	0.799**	0.123*	1			
	Sig. (2-tailed)	0.000	0.000	0.000	0.014				
	N	396	396	396	396	396			
EC	Pearson Correlation	−0.537**	0.397**	−0.538**	−0.260**	−0.593**	1		
	Sig. (2-tailed)	0.000	0.000	0.000	0.000	0.000			
	N	396	396	396	396	396	396		
Temperature	Pearson Correlation	−0.644**	0.058	−0.006	0.024	−0.280**	0.210**	1	
	Sig. (2-tailed)	0.000	0.249	0.906	0.640	0.000	0.000		
	N	396	396	396	396	396	396	396	
Root Collar Diameter	Pearson Correlation	0.192**	−0.193**	0.290**	0.013	0.304**	−0.109*	−0.103*	1
	Sig. (2-tailed)	0.000	0.000	0.000	0.791	0.000	0.031	0.041	
	N	396	396	396	396	396	396	396	396

**Correlation is significant at the 0.01 level (2-tailed)

* Correlation is significant at the 0.05 level (2-tailed)

Test: Correlation Analysis

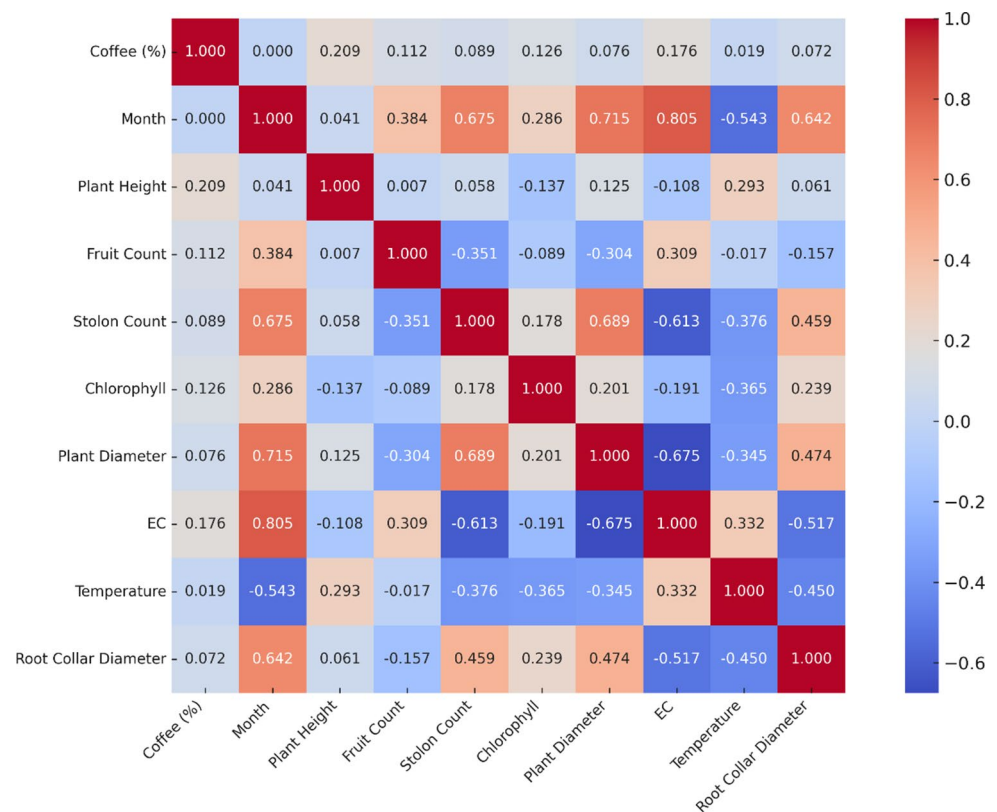
correlation with stolon quantity ($r=0.178$, $p<0.01$) and plant diameter ($r=0.689$, $p<0.01$), whereas elevated electrical conductivity adversely impacted stolon development ($r=-0.613$, $p<0.01$). These findings offer significant insights to enhance the impact of coffee concentration, duration, and soil conditions on plant development and productivity (Table 7; Fig. 7).

The analyses revealed a 9.25% reduction in plant height, a 39.20% increase in fruit count, a 23.93% decrease in stolon count, a 1.36% decrease in chlorophyll content, a 13.78% reduction in plant diameter, and a 9.42% increase in root collar diameter for *F. ananassa* in the growing media containing 20% coffee ground compared to the medium devoid of coffee ground. In the substrate containing 50% coffee ground, plant height diminished by 13.58%, fruit count augmented by 45.81%, stolon count decreased by 18.71%, chlorophyll concentration declined by 40.34%, plant diameter reduced by 10.49%, and root collar diameter increased by 4.79% relative to the substrate devoid of coffee ground.

Despite hundreds of scientific studies on the ecological and economic benefits they provide, green roofs are still too expensive, luxurious and far from being a necessity in many

parts of the world. There may be many different reasons for this situation. However, whatever the reason, the need for green roofs to be more accessible to everyone and to be built in more sustainable ways is inevitable, especially when climate change is a significant challenge nowadays. Although green roofs are purposely built to include plants and provide ecological benefits (Mihalakakou et al. 2023), it is possible to say that green roofs, which need to be constantly watered, where natural resource values such as soil are used intensively, and where maintenance and built costs are high, have some problems in compatibility with their purpose. The existence of such conflicting approaches regarding green roofs has the potential to create an obstacle to their widespread use. Pratama et al. (2023) claims policies and bureaucratic obstacles, high costs and technological difficulties are the main factors preventing the spread of green roofs. This situation can be considered as an indicator that there is still an intense need for scientific studies to make green roofs widespread.

One of the most important problems that the world has to face due to many reasons, especially climate change and increasing world population, is access to safe food.

Fig. 5 Correlation heat map for *S. spurium*

Moreover, this problem concerns a very wide area, from developing countries (Sani and Kemaw 2019) to countries that have completed their development (Long et al. 2020). While the situation is so sensitive and changing living conditions can take this sensitivity to much higher levels, it would be a very reasonable approach to consider green roofs as edible surfaces in cities (Ristianti et al. 2024; Russo and Cirella 2020). From this perspective, the fact that one of the plant materials of this research is strawberry plant alone with *S. spurium* can be considered both as a move to meet an important ecosystem service and as a strong motivation to break the prejudices of local people against green roofs. Moreover, with an impressive approach to the research, the recycled material was treated as an addition to the substrate just like some studies do (Eksi et al. 2015; Farrell et al. 2012; Griffin et al. 2017; Petreje et al. 2023; Xue and Farrell 2020), unlike studies that use recycled material

as an inorganic layer such as drainage layer etc. (Baryła et al. 2024; Jiang et al. 2024; Kazemi et al. 2023). When focusing on the use of coffee ground, the studies like a search of a sustainable substrate for green roofs by using coffee ground together with biochar (Haeldermans et al. 2023), an energy saving architectural material (Saeli et al. 2023) and a substrate that contributes to the removal of pollutants in green walls (Pradhan et al. 2019) can also be seen, which are also so important.

As for *S. spurium*, another species that forms the material of the research, it is a popular species that has been frequently used in the scientific studies on green roofs (Cotoz et al. 2023; O'Carroll et al. 2023; Varela-Stasinopoulou et al. 2023). This popularity of the plant may be due to the fact that the *Sedum* genus has spontaneously grown on roofs since the early periods of history and, accordingly, it was frequently used on roofs for different purposes by humanity in the same periods.

In this study, based on the data obtained, testing the use of coffee grounds in future studies and applications for green roofs utilizing *F. ananassa* plants appears appropriate, mainly when focusing on fruit yield while the species were already evaluated on green roof studies before (Xie et al. 2020). In fact, the need for such studies is quite high. Because although strawberry farming is considered very suitable for urban areas with different techniques like vertical farming, this attempt is quickly abandoned due to the

Table 6 OneWay ANOVA results for *F. Ananassa*

Coffee (%)	0	20	50
Plant Height	11.553b	10.484a	9.984a
Fruit Count	2.530a	3.522ab	3.689b
Stolon Count	2.469b	1.878a	2.007ab
Chlorophyll	48.646b	47.983b	29.022a
Plant Diameter	47.227a	40.719a	42.272a
EC	1.055a	1.126a	1.340b
Soil Temperature	24.254a	24.497a	24.553a
Root Collar	12.745a	13.946b	13.356ab

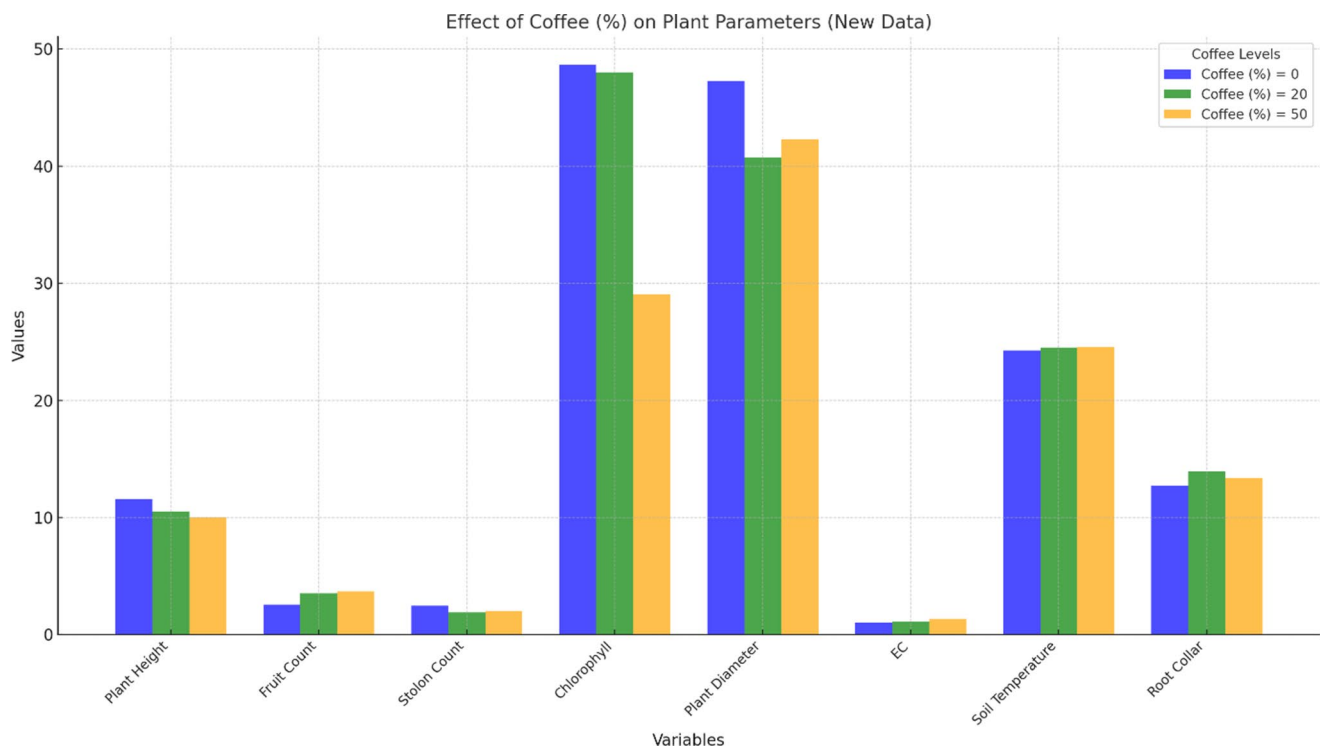


Fig. 6 Effect of coffee (%) and *F. ananassa* plant parameters

lack of knowledge on this subject and the lack of information between commercial strawberry growers and the new generation urban farmers (Kouloumprouka Zacharaki et al. 2024). Therefore, research on the use of species belonging to the genus *F. ananassa* on green roofs can be an initiative both for the known benefits of green roofs and for the problems related to strawberry farming in urban areas.

One of the most curious topics regarding the research is whether there is a relationship between the amount of coffee ground in the substrate and the coverage density for *F. ananassa*, which is one of the most important expectations in green roofs. However, for coverage density criteria, coffee ground rate in the substrates neither positively nor negatively affect outcomes. While this study indicates an inverse relationship between coverage density and coffee ground ratios for *S. spurium*, which is commonly used in green roofs, the observed relationship with plant height suggests that reassessing such studies with varied parameters could enhance the efficient utilization of global resources and waste management strategies. As physical characteristics like plant height and coverage on green roofs are important to reduce the effects of negative environmental consequences, it is possible to say that more studies on this subject will be needed in the future.

Given current global resource consumption rates, evaluating waste materials, even if they do not surpass soil as a growing medium, is justified for their potential contribution to soil conservation through waste prevention. Therefore,

coffee grounds should be considered a promising alternative substrate, and future research focusing on the performance of other waste materials could be particularly beneficial. In their 2020 study, Sutanto et al. (2020) observed that applying coffee grounds as fertilizer increased coffee plants' yield and shoot length in Indonesia. Similarly, our study found that increasing the coffee ground level led to higher fruit yield in *F. ananassa* plants and increased shoot length in *S. spurium* plants. Shenoy et al. (2011) emphasized that utilizing agricultural waste, such as coffee grounds, in various applications could mitigate environmental pollution and enhance agricultural value. Our study shares this objective. (Rahmah et al. 2023) demonstrated that using coffee grounds as fertilizer significantly reduces CO₂ emissions. Their research on green coffee bean production suggests a positive impact on product quality. Given Indonesia's substantial contribution to global coffee production, utilizing coffee grounds could help reduce global CO₂ emissions. Our study similarly found that coffee grounds positively influence fruit development in *F. ananassa* plants. The additional structural load from growing media and plants on green roofs poses a drawback (Başçğımez 2019). This study calculated that growing media incorporating coffee grounds was 4.12% lighter than 100% soil with 20% coffee grounds and 7.79% lighter with 50% coffee grounds. Thus, utilizing coffee grounds mitigates concerns regarding structural load.

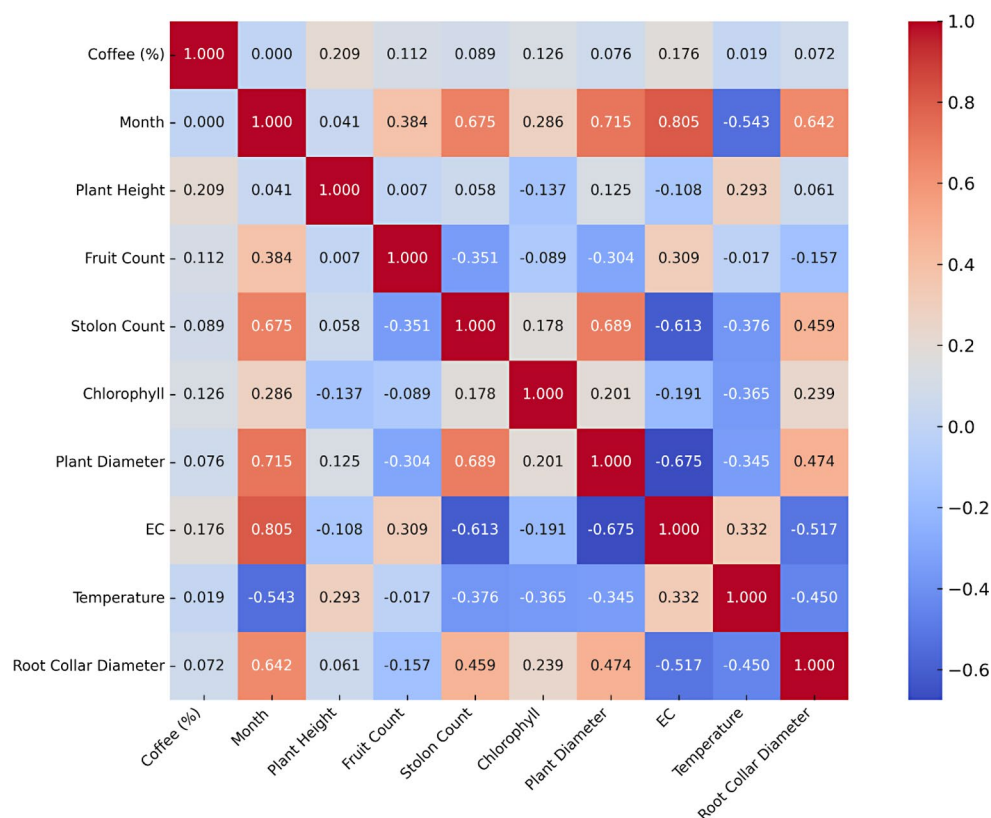
Table 7 Inter-parametric correlation analysis

		Coffee (%)	Month	Plant Height	Fruit Count	Stolon Count	Chlorophyll	Plant Diameter	EC	Temperature	Root Collar Diameter
Coffee (%)	Pearson Correlation	1									
	Sig. (2-tailed)										
	N	396									
Month	Pearson Correlation	0,000	1								
	Sig. (2-tailed)	1.000									
	N	396	396								
Plant Height	Pearson Correlation	0.209**	0.041	1							
	Sig. (2-tailed)	0.000	0.411								
	N	396	396	396							
Fruit Count	Pearson Correlation	0.112*	0.384**	0.007	1						
	Sig. (2-tailed)	0.026	0.000	0.886							
	N	396	396	396	396						
Stolon Count	Pearson Correlation	0.089	0.675**	0.058	−0.351**	1					
	Sig. (2-tailed)	0.078	0.000	0.247	0.000						
	N	396	396	396	396	396					
Chlorophyll	Pearson Correlation	0.126*	0.286**	−0.137**	−0.089	0.178**	1				
	Sig. (2-tailed)	0.012	0.000	0.006	0.077	0.000					
	N	396	396	396	396	396	396				
Plant Diameter	Pearson Correlation	0.076	0.715**	0.125*	−0.304**	0.689**	0.201**	1			
	Sig. (2-tailed)	0.130	0.000	0.013	0.000	0.000	0.000				
	N	396	396	396	396	396	396	396			
EC	Pearson Correlation	0.176**	0.805**	−0.108*	0.309**	−0.613**	−0.191**	−0.675**	1		
	Sig. (2-tailed)	0.000	0.000	0.031	0.000	0.000	0.000	0.000			
	N	396	396	396	396	396	396	396	396		
Temperature	Pearson Correlation	0.019	−0.543**	0.293**	−0.017	−0.376**	−0.365**	−0.345**	0.332**	1	
	Sig. (2-tailed)	0.703	0.000	0.000	0.738	0.000	0.000	0.000	0.000		
	N	396	396	396	396	396	396	396	396	396	
Root Collar Diameter	Pearson Correlation	0.072	0.642**	0.061	−0.157**	0.459**	0.239**	0.474**	−0.517**	−0.450**	1
	Sig. (2-tailed)	0.152	0.000	0.228	0.002	0.000	0.000	0.000	0.000	0.000	
	N	396	396	396	396	396	396	396	396	396	396

**Correlation is significant at the 0.01 level (2-tailed)

* Correlation is significant at the 0.05 level (2-tailed)

Test: Correlation analysis

Fig. 7 Correlation heat map for *F. ananassa*

Conclusion and recommendation

Although the research concluded that coffee waste is not significantly supportive growth media than soil for plant development, it does contribute to plant growth. Examples include the increase in plant height in *S. spurium* and the number of fruits in *F. ananassa* with higher amounts of coffee in the growth media. Coffee contributes to structural stability due to its mass and aids in water retention during droughts, thereby supporting its utilization as a growth medium rather than its disposal as trash. Additionally, the research shows that plants continue to grow and produce fruit without additional irrigation, underscoring the beneficial properties of coffee waste for plant cultivation.

Given these considerations, it is recommended that coffee grounds be utilized as a growth media to reduce the static load on roofs and recycle coffee waste that would otherwise contribute to environmental pollution. This approach can also positively impact recycling efforts.

Soil formation is a lengthy and resource-intensive process compared to artificial growth media, which requires unsustainable maintenance. Thus, utilizing waste materials like coffee grounds, known for supporting plant survival and development without adding weight, aligns green roofs more closely with their intended ecological purposes. Despite potential concerns over maintenance requirements and carbon emissions from growth media, the environmental

benefits of green roofs are enhanced by using waste materials like coffee grounds.

Using coffee grounds as a growth media significantly impacts strawberry plants and opens new possibilities for edible landscapes in urban areas. Access to safe food is crucial in combating the climate crisis and reducing climate control costs, with its importance likely to grow. Moreover, since coffee grounds are inherently safe for edible plants, their use as a growth media poses no adverse effects, transforming waste into a valuable resource and promoting the concept of an alternative and safe “edible garden.”

In addition to their application on green roofs, coffee grounds can enhance fruit yield in areas dedicated to fruit production. While green roofs are essential for urban ecosystems, their practical implementation can be challenging, necessitating maintenance, irrigation, and organic matter supplementation. These factors have led to the cautious adoption of green roofs, exacerbated by concerns such as structural load and unwanted wildlife support in some communities. Therefore, exploring alternative growth media and experimenting with edible plants on green roofs are critical to overcoming societal resistance. Green roofs should require minimal irrigation and maintenance, aligning with their original purpose.

Based on this information, the study’s recommendations are as follows:

1. Green roofs should evolve into user—and budget-friendly solutions by minimizing resource-intensive features dominated by exotic plants. This research aims to advance in that direction. The performance of coffee grounds as a growth media and the psychological impact of waste recycling is expected to foster broader acceptance of green roofs across diverse sociocultural groups. In this way, it will be possible to make green roofs more popular phenomena about in daily life and to make it easier for them to become a natural part of life.
2. The movement towards the use of coffee grounds on green roofs should be encouraged with the “edible green roof” movement, thus creating a new perspective in the eyes of the public who have stayed away from green roofs until now, as well as access to safe food. The idea of an edible green roof using organic waste can be a strong enough motivation for an audience that has never taken action until now.
3. Green roofs should transcend their role as mere marketing tools or greenwashing efforts and instead aim to restore natural habitats within urban environments. The focus should be on creating habitats that provide shelter and food for wildlife while being compatible with local architecture and climatic conditions. Achieving this goal requires addressing green roofs’ negative ecological and economic costs despite their aesthetically pleasing outcomes. Coffee grounds’ cost-reducing, eco-friendly properties and support for edible plants align well with these objectives.
4. Further performance testing of various waste materials and diversifying the plant species studied on green roofs is recommended. Given the rapid decline of pollinators, reducing direct interventions in agricultural economics and establishing alternative farming areas are critical imperatives. Despite its significant environmental impact, coffee farming remains a primary industry that is unlikely to diminish soon. Therefore, repurposing limited-use waste products like coffee grounds to create habitats for pollinators represents a logical approach.
5. Green roofs predominantly featuring edible plants are particularly suitable for public buildings such as schools and hospitals, potentially initiating a new trend. They can catalyze action, support educational initiatives, and enhance ecosystem services. Moreover, using coffee grounds produced within these buildings as growth media for green roofs can increase visibility and foster an emotional connection between users and green roof environments.
6. While widely used global green roof plants like *Sedum* are widespread, numerous alternative plant species

suitable for different regions exist. Transitioning from monocultural green roof surfaces to region-specific vegetation reduces maintenance costs and lays crucial foundations for integrating green roofs into local cultures. Encouraging research on the performance of various growth media, including coffee grounds with diverse plant combinations, will facilitate the incorporation of green roofs into everyday urban life.

In conclusion, with their structural stability and water retention properties, coffee grounds can effectively serve as a growth media on green roofs, mitigating their disposal as waste. Our research data supports reconsidering coffee grounds as valuable resources rather than waste products.

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Declarations

Ethical approval Ethical approval is not required for this research.

Consent to participate Our participation is completely voluntary.

Consent for publication We give our consent for information about all authors relative to be published in Urban Ecosystems.

Conflict of interest The authors declare no conflict of interest.

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