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Urban Food and Nutrition Security Resilience through Urban Agriculture

A Circular Economy Approach

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Keywords: urban agriculture, informal settlements, climate smart gardens, frass fertilizer, food and nutrition security, household welfare, food production, gender equality

JEL codes: I31, N57, Q12, Q15, Q18, Q53

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Study pre-registration

AEA RCT Registry no. AEARCTR-0011089 at https://www.socialscienceregistry.org/trials/11089

Declaration of interest

The authors report that there are no competing interests to declare.

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1. Introduction

Currently, about 55% of the world's population (4.4 billion people) lives in urban areas, with developing countries experiencing rapid growth in informal settlements due to this trend. Rapid urbanization has outpaced the development of affordable housing, critical infrastructure including water, waste management and sanitation, and essential social services, amplifying development challenges (Ayuya, 2024; Li et al., 2023; Macrotrends, 2025; Soma et al., 2022; United Nations, 2024). By 2022, informal settlements in sub-Saharan Africa housed 53.6% of the urban population (265 million people), rising from 50.2% in 2020, with projections estimating an increase of an additional 360 million people by 2030 (Our World in Data, 2025; United Nations, 2024).

Informal settlements often feature poor infrastructure, unemployment and high poverty rates, which exacerbate food and nutrition insecurity, malnutrition, and related health issues (Ayuya, 2024; MacHaria et al., 2018; Mkhize et al., 2023). This threatens the achievement of Sustainable Development Goal (SDG) 2 – zero hunger, which encompasses ending food and nutrition insecurity and promoting sustainable agriculture. Hence, more effective strategies are needed to achieve SDG 2 and to improve the welfare of vulnerable populations (Russell et al., 2018).

In Kenya, approximately 40.5% of the urban population (6.6 million people) lived in informal settlements in 2022. These settlements are characterized by high levels of food and nutrition insecurity (Kimani-Murage et al., 2014; Our World in Data, 2025), which contribute significantly to malnutrition (Kimani-Murage et al., 2015), particularly during crises such as post-election violence and the COVID-19 pandemic (Ayuya, 2024; Kimani-Murage et al., 2014; Kiribou et al., 2024; Mkhize et al., 2023). For instance, the food poverty rate in urban areas rose sharply from 22.5% in 2019 to 33.0% in 2020, a notably higher increase compared to rural or national figures, indicating how such crises disproportionately affect informal settlement dwellers (Kenya National Bureau of Statistics, 2024).

Urban agriculture in the form of urban farming has emerged as a practical solution to address food and nutrition insecurity in informal settlements because it improves food access, dietary diversity, and nutritional status (Ali et al., 2019; Averbeke, 2007; Garbero & Jäckering, 2021; Kimani-Murage et al., 2014; Mkhize et al., 2023; Vandevijvere et al., 2010; Warren et al., 2015). More specifically, urban and peri-urban agriculture including horticulture plays a crucial role in supplying nutrient-dense, perishable foods such as African indigenous vegetables, which significantly benefits vulnerable urban populations (Ambrose-Oji, 2009; Kiribou et al., 2024). Indigenous vegetables offer culturally appropriate, affordable, and efficient sources of micronutrients, thus addressing nutritional deficiencies prevalent among the urban poor (Yang & Keding, 2009).

Empirical evidence from cities located in East Africa and Cameroon shows that urban agriculture benefits both urban livelihoods and household food supply (Lee-Smith, 2010) by significantly supporting dietary needs, enhancing child health, and generating income. Studies from Nakuru, Dar-es-Salaam, Kampala, and Yaoundé illustrate urban agriculture's notable impact on food and nutrition security (Lee-Smith, 2010). Various studies conducted in Kenya investigate the nexus between urban farming, rural farming, and food security, although with mixed results. Foeken and Owuor (2008) found that in Nakuru, the urban poor were underrepresented in urban agriculture and that rural agriculture was more beneficial to urban-based households than urban agriculture. Nevertheless, Omondi, Oluoch-Kosura, and Jirström (2017) reported a positive correlation between urban agriculture, urban-based rural agriculture, and food security in Thika and Kisumu. Gallaher, Kerr, Njenga, Karanja, and WinklerPrins (2013) found that households in Kibera practicing urban agriculture by means of sack gardening felt more food secure, consumed more types of vegetables, and saw increased levels of social capital compared to households that did not practice urban agriculture. Similarly, using a multi-method qualitative approach, Otieno et al. (2025) found that vertical gardening in Kibera improved food security, strengthened household resilience, and empowered women, but its scalability was limited by land, water, and institutional constraints.

Urban agriculture's role in urban food systems is well recognized, however persistent issues related to food access, affordability, safety, and quality remain critical concerns in Kenya. Downs et al. (2022) emphasize these challenges, highlighting the important influence of environmental factors and individual barriers such as income constraints on food choices in Nairobi's informal settlements. Additionally, Ahmed et al. (2019) note significant hygiene risks and infrastructure inadequacies affecting vendors and food safety in Kibera, Mathare, and Mukuru settlements. Tendet, Makalliwa, and Sagwe (2024) further demonstrate the food security benefits of urban agriculture while raising concerns regarding food safety risks associated with farming locations and agricultural inputs. These studies collectively emphasize the necessity of integrating food safety, environmental management, and sustainable practices within urban agriculture frameworks.

Zivkovic et al. (2022) highlight both the potential and challenges of group-based, nutrition-sensitive urban agriculture interventions in low-resource urban settings. The authors underscore the need to address water scarcity, labor demands, and consistent engagement to achieve significant improvements in dietary diversity. Several challenges constrain urban agriculture in low-income informal settlements, including water scarcity, pests and diseases, knowledge gaps, land access, financial constraints, and weak policy support (Ahmed et al., 2019; Bisaga et al., 2019; Kiribou et al., 2024; Tendet et al., 2024; Zivkovic et al., 2022). However, these challenges simultaneously represent opportunities to promote household welfare, the empowerment of women, targeted training, context-appropriate farming practices, improved input access, and integrated resource management. Among these challenges, waste management and sanitation are particularly pressing, yet they also present a considerable opportunity for the implementation of sustainable urban agriculture practices. Formal waste systems are largely absent in informal settlements, and organic waste, which constitutes about 70% of Nairobi's solid waste, remains mostly unmanaged, posing severe health and environmental risks (Lee-Smith, 2010).

Kiribou et al. (2024) argue that urban agriculture offers significant opportunities for sustainable urban development through nature-based solutions. These solutions include reducing flood risks, stabilizing soils, improving air quality, enhancing biodiversity, mitigating urban heat stress, and supporting climate resilience. Additionally, urban agriculture facilitates carbon sequestration, opportunities for nutrient recovery, water conservation through localized reuse, and revitalization of underutilized land, creating essential urban environmental benefits (De Neergaard et al., 2009; Kiribou et al., 2024; Lee-Smith, 2010). However, recycling urban waste for agriculture, while offering nutrient recovery opportunities, also introduces health and environmental risks, underscoring the need for regulated and pragmatic waste management approaches (De Neergaard et al., 2009).

Aligning with circular economy principles, black soldier fly (BSF; Hermetia illucens) larvae composting is a promising technology that has the potential to address this concern by converting organic waste into valuable products, such as nutrient-rich frass fertilizer (Abd Manan et al., 2024; Lopes et al., 2022). Empirical evidence supports BSF frass fertilizer's effectiveness in enhancing crop growth, yield, and nutritional quality across various contexts (Anyega et al., 2021; Awad et al., 2024; Beesigamukama et al., 2020; Tambeayuk et al., 2024; Tanga et al., 2022; Terfa, 2021).

Despite these benefits, challenges still persist, including inconsistent BSFFF quality due to varied feed substrates, lack of standardized application guidelines, limited real-world trials that rely on short-term or plot-scale studies, sparse data from low-income settings - particularly among vulnerable urban populations, and inadequate research on socio-economic and agronomic feasibility (Abd Manan et al., 2024; Anyega et al., 2021; Awad et al., 2024; Beesigamukama et al., 2020; Tanga et al., 2022; Terfa, 2021).

Leveraging the circular economy approach, this study contributes to addressing these knowledge gaps by evaluating BSFFF's effectiveness as an organic fertilizer that can promote urban food and nutrition security within informal urban settlements. Very few studies investigate the link between urban agriculture and household waste management practices. Those that do use qualitative data to show the potential benefits of using organic waste in urban agriculture for sustainable food production (Lal, 2020; Menyuka et al., 2020). This study reinforces BSFFF as a climate-smart, health-conscious waste management and sanitation solution in understudied urban areas. In addition, this study provides locally relevant agronomic data to support tailored recommendations in the context of small-scale urban agriculture. The study also demonstrates the dual benefits of waste reduction and improved crop production, and offers context-specific insights relevant to densely populated urban areas facing significant waste management and sanitation challenges (Gamage et al., 2024; Gunapala et al., 2025). Furthermore, this study introduces context-specific insights from densely populated urban environments characterized by abundant organic waste, limited formal agricultural inputs, and significant food and nutrition security challenges.

Additionally, to strengthen causal evidence lacking in the existing literature (Swanepoel et al., 2021; Warren et al., 2015), this study employs a cluster randomized controlled trial (RCT) design to enhance causal inference, which offers stronger evidence of the impact of urban agriculture on food and nutrition security than similar studies conducted using qualitative methods (Otieno et al., 2025). Conducted in the largest urban informal settlement in sub-Saharan Africa, situated in Kibera, Nairobi, the study evaluates the impact of urban agriculture innovations including climate smart gardens (CSG) and BSFFF and provides actionable insights for policy and practice.

The study also investigates gendered effects of the proposed interventions. Women are central actors in the provision of food at the household level and are crucial in translating agricultural output and income into household food and nutrition security. However, women often face gender-based barriers in urban agriculture, including limited access to land, inputs, and credit, which contributes to lower productivity and reduced benefits from food production, reinforcing gender gaps in food and nutrition security (Phillips et al., 2025).

Gendered effects of urban farming have mostly been discussed descriptively in the literature (Poulsen et al., 2015). Urban agriculture may play a vital role in fostering women's empowerment for several reasons. First, it appeals to women logistically, since urban farming is typically carried out at home. Second, urban agriculture is easily integrated with other household responsibilities, since it requires fewer resources in terms of land, water, and time. Lastly, farming at home offers a viable solution to land tenure challenges that women face in accessing, using, and controlling land in urban settlements (Bisaga et al., 2019; Blessing, 2019; Kutiwa et al., 2010; Poulsen et al., 2015; Suchá & Dušková, 2022; Surya et al., 2020).

In addition to primarily informing the achievement of SDG 2 (zero hunger, including ending food and nutrition insecurity and promoting sustainable agriculture), the study's findings also provide important insights towards achieving multiple other SDGs, including SDG 1 - no poverty, SDG 3 - good health and well-being, SDG 5 - gender equality, SDG 6 - clean water and sanitation, SDG 11 - sustainable cities and communities, SDG 12 - responsible consumption and production, and SDG 13 - climate action (United Nations, 2024). The study offers policy recommendations to enhance policies regarding food and nutrition security, sustainable waste management, poverty reduction, and gender equality.

The rest of the paper proceeds as follows: Section 2 describes the theoretical framework. Section 3 provides the experimental design. Section 4 describes the empirical strategy. Section 5 presents and discusses the empirical findings, and Section 6 summarizes the conclusions and offers policy recommendations.

2. Theoretical framework

This study employs the Gronau-type household production model as its guiding framework (Gronau, 1977). Since a household may allocate resources to producing or purchasing food, this model allowed us to take into consideration the opportunity cost of time, income budget constraints, and technical changes and efficiency in household production as determinants of the demand for food. The goal was to assess how the introduction of urban agriculture, including CSGs (a change in household production capital) and the provision of BSFFF (a change in technical efficiency of the production technology), affects food production and purchasing decisions, and how this ultimately impacts food and nutrition security.

The household's problem is to maximize a utility function from two goods, leisure, l, and food, x, which can either be produced at home, denoted by x_H, or purchased in the market, denoted by x_M, at a price p. The utility function $U = u(x, l)$ is assumed to be strictly concave, and the household is assumed to value total consumption of food $x = x_H + x_M$ rather than individual quantities of home-produced and purchased food.

Time spent working is denoted by t_M at a fixed wage rate of w. Goods are produced at home using the production function $x_H = f(t_H|k, \varphi)$, where production depends on the endogenous choice of time spent working at home t_H, as well as on exogenous capital k and a technology efficiency parameter φ. The production function f is further assumed to exhibit decreasing marginal productivity ($f' > 0$ and $f'' < 0$) and to satisfy $f(0|K, \varphi) = f(t_H|0, \varphi) = 0$, so that $k = 0$ or $t_H = 0$ is equivalent to $x_H = 0$, i.e., without capital and dedicating time to working at home, food production at home is equal to zero. The household faces two constraints: the time constraint $T = t_H + t_M + l$ and the endogenous budget constraint $px_M = wt_M$, where income derived from wage work, wt_M, is used to purchase food in the market, px_M.

The necessary conditions for an interior optimum call for the marginal product of work at home to equal the marginal rate of substitution between food and leisure time, which in turn equals the shadow price of time (w^*). If the individual works in the market ($t_M > 0$), that condition will also equal the real wage rate as follows:

$$\frac{\partial U/\partial l}{\partial U/\partial x} = f' = w = (w^*) \quad (1)$$

The first-order conditions of this problem allow us to determine the implicit household optimal demand functions for time spent on work at home t_H^*, home production x_H^*, food purchases x_M^*, and the household's labor supply t_M^*; all of which are a function of real wage w/p and the other exogenous parameters, k and φ.

One usual prediction of this model is that if p increases, the real wage rate reduces and unambiguously increases both the amount of time allocated to food production at home and the quantity of food produced at home. However, should capital be so low as to make production at home infeasible, i.e. $x_H = 0$, the total impact on food consumption ($x = x_M$) is determined by the resulting substitution and income effect, which could potentially decrease total food consumption and thus hamper food and nutrition security.

Two other comparative statics with respect to k and φ allow us to determine the main relationships of interest to our study. The introduction of CSGs can be modeled as a discrete jump in k, and the administering of instructions on how to use of BSFFF is modeled as a change in φ, since better information and training in a household is connected to the efficiency of household production (Becker, 1965; Huffman, 2011; Michael & Becker, 1973).

A change in k from $k = 0$ (no farming equipment) to $k > 0$ is predicted to lead to food production at home, although it is true that with $k > 0$, if the marginal productivity of work at home falls short of the real wage, there would be no food production at home and the household would be faced with the previous dichotomy of work in the market and leisure. As for the use of BSFFF, provided that with $k > 0$ the household produces food at home, an increase in φ entails an increase in marginal productivity of food at home for all levels of t_H, which therefore leads to an increase in the amount of time allocated to food production at home and quantity of food produced at home.

In sum, the first-order conditions guided our construction of the econometric models employed in our analysis. The comparative statics with respect to k and φ allowed us to envisage the direction of change of food demand as a result of introducing urban agriculture equipment including CSGs, and as a result of increasing the efficiency of production through the provision of BSFFF. The main outcome variables of interest that give us a measure of food and nutrition security are food purchases x_M and food production x_H, which are combined to produce total food consumption x. A secondary variable of interest includes time spent on food production at home t_H.

3. Experimental design and data collection

3.1 Intervention

This study included two interventions. The first intervention provided households with CSGs, including starter inputs of kale and spinach seedlings, along with training on CSG management (Treatment 1). The second intervention combined the provision of CSGs with BSFFF and offered training on the use of both inputs (Treatment 2).

Generally, CSGs are a low-cost innovative vertical gardening solution used for growing many plants in a very small space. A four-terraced CSG formed of circular rings with a base diameter of 3.5 feet occupies 1 m^2 and provides a planting area of approximately 0.003 acres. It accommodates up to 90 vegetable plants, compared to the 16 plants that can be grown in one square meter under traditional farming. Each CSG requires a maximum of 20 liters of water for each irrigation cycle. Seedlings are watered twice a day until established, then once daily. Mature plants are watered two to three times a week. A CSG can produce up to 5 kg of vegetables per week for 16 weeks (4 months). After that period, the topsoil is removed and the remaining soil is mixed with organic fertilizer for replanting. A CSG costs about $25 to install and lasts around 10 years.

Informal settlements such as Kibera contend with poor waste management and sanitation infrastructure. However, solid waste management recycling improves sanitation through the circular economy approach. Essentially, BSFFF production involves the use of BSF larvae to recycle household waste (including plant waste, solid waste, liquid waste, and human waste) to produce frass fertilizer (Abro et al., 2020). This study used certified BSFFF from Regen Organics – an enterprise that recycles human waste from informal settlements including Kibera into low-cost fertilizer. A 50 kg bag of frass fertilizer costs $18, and each CSG uses 2.5–3 kg.

The BSFFF production model includes the use of innovative low-cost toilets developed as a sanitation solution for informal settlements. These toilets offer a substitute for pit latrines and "flying toilets," where people use plastic non-biodegradable bags to collect human waste and then toss the bags away indiscriminately, creating sanitation hazards. These low-cost toilets, which use a container-based dry technology requiring no water or electricity, are franchised as shared community facilities or businesses.

3.2 Experimental design

The study used a cluster RCT to investigate the impact of urban farming including CSGs and BSFFF on food and nutrition security, household welfare, and food production. We used 150 enumeration areas (EAs), including 25 EAs located in each of the six sub-locations that form the administrative boundaries of the Kibera informal settlement. The sub-locations included Kibera, Lindi, Makina, Gatwekera, Olympic/Kianda, and Laini Saba (Figure 1).

We randomly assigned three conditions in each sub-location, including CSGs only, CSGs and BSFFF, and the control condition. With the help of village elders and community health volunteers, we recruited a maximum of six households in each EA, targeting a sample of 750-900 households. This sample size provided us with 80% power to detect a minimum increase of $2.50 (KES 375) in weekly food consumption expenditure. The power calculation assumed a 5% level of statistical significance based on a weekly food expenditure of $10 (KES1,426). This benchmark value for the outcome indicator was drawn from the 2015/16 Kenya Integrated Household Budget Survey (Kenya National Bureau of Statistics, 2018).

Figure 1. Research design

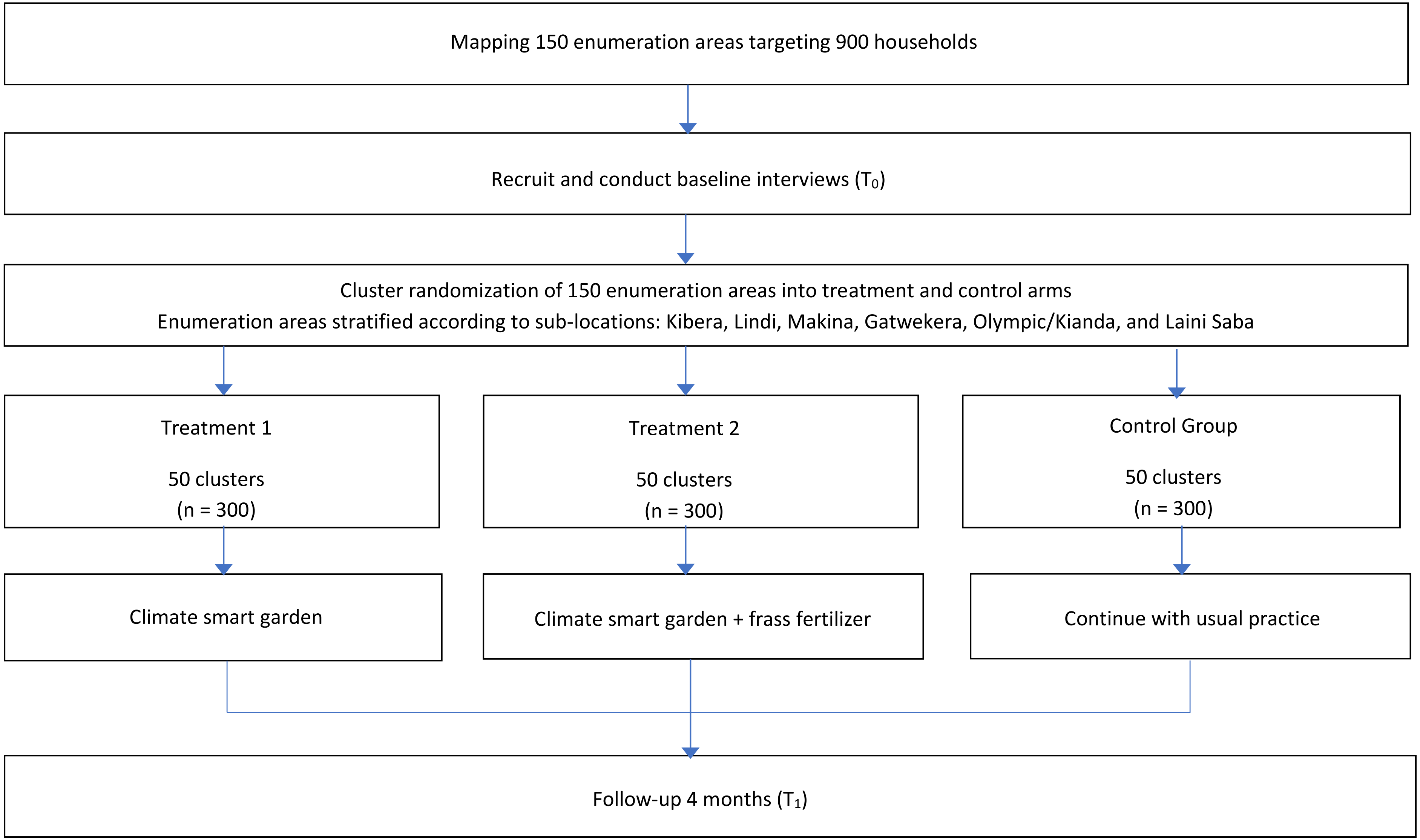
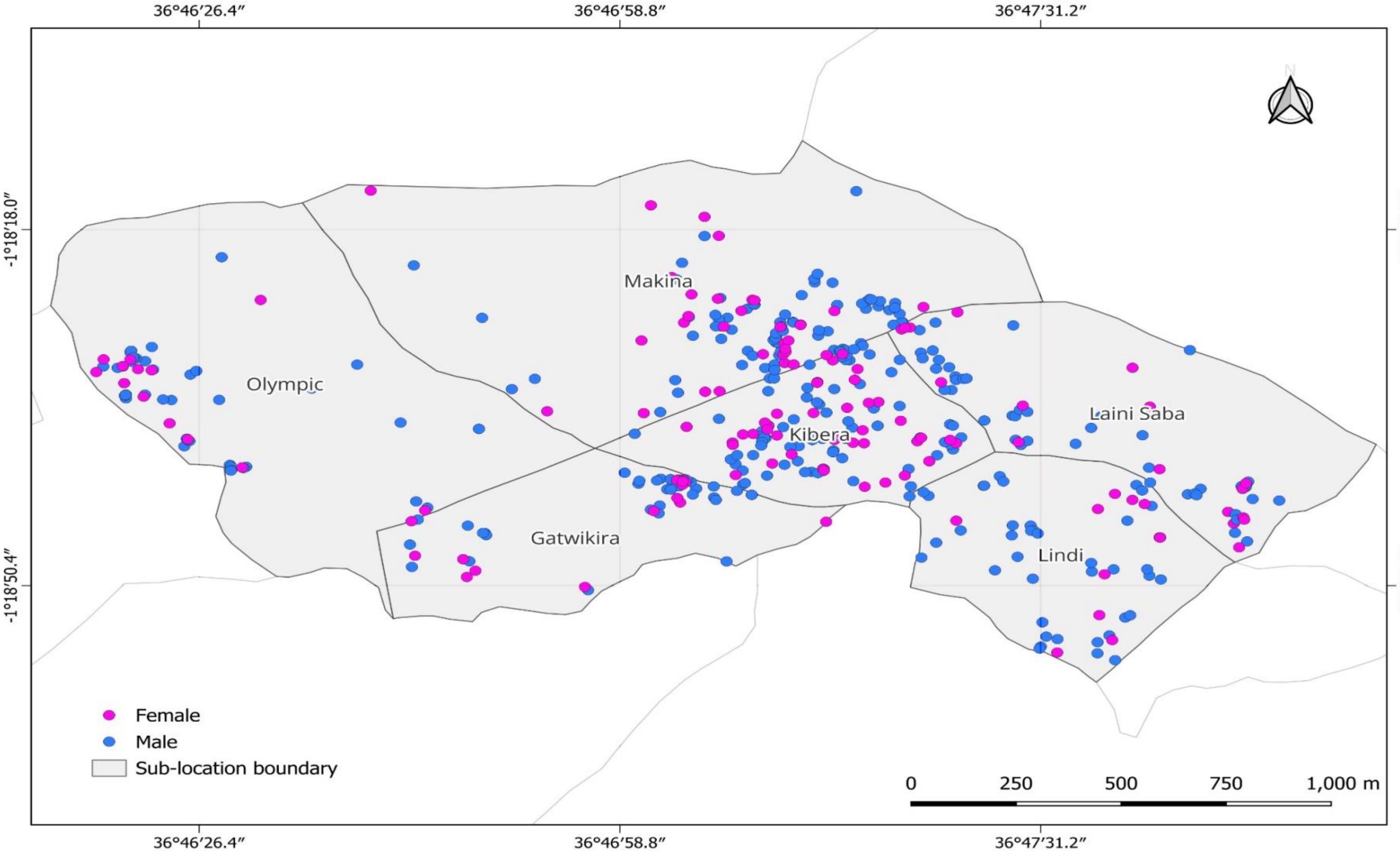


Figure 2. Household listing by female and male headship



3.3 Data collection and processing

Kibera, a locality situated in Nairobi County, is the largest urban informal settlement in sub-Saharan Africa. It covers an area of approximately 2.1 km^2 and is home to an estimated 120,057 people according to the 2019 census reports. However, various studies report that the population actually stands at about one million, making it the most densely populated settlement in Kenya (Meredith et al., 2014). The majority of the residents of Kibera live in extreme poverty. The settlement is also characterized by high unemployment, poor infrastructure, and a lack of basic urban services including running water, sanitation, electricity, health care, transport, and solid waste management, among others (Meredith et al., 2014).

In May 2023, we carried out a mapping exercise in Kibera's sub-locations and compiled a household listing (Figure 2). We conducted the baseline survey in June 2023, implemented the interventions in mid-June and July 2023, and carried out the endline survey in November 2023, approximately four months after the interventions. Generally, the planting-to-harvesting cycle for kale and spinach takes about six weeks, allowing for three growth cycles within the study period.

During the household listing, respondents were asked about their interest in participating in the project, including the use of CSGs and BSFFF. Enumerators assessed the proposed space that the CSG would occupy when respondents were willing to participate. Enumerators also explained the potential provision of BSFFF and its production process. Resistance was minimal, likely due to familiarity with Regen Organics toilets in Kibera. At baseline, 28 households reported using their own organic fertilizer in their home gardens, whereas only 10 refused frass fertilizer because it was derived from human waste.

The baseline survey instrument collected data on household demographics, food production characteristics, and the outcomes of interest, including the food insecurity experience scale (FIES), food insecurity incidence, household dietary diversity (HDD), household welfare including food consumption expenditure and total consumption expenditure, food production, and time spent on food production. The endline survey instrument collected data on the outcome variables and additional data on urban agriculture practices.

Table 1. Summary statistics, baseline

Variable	Mean	Std. Dev.	Min	Max
Food insecurity experience scale	7.332	3.542	0.00	10.00
Food insecurity incidence	0.745	0.436	0.00	1.00
House dietary diversity	0.366	0.482	0.00	1.00
House dietary diversity scale	7.410	2.331	0.00	12.00
Vegetable consumption expenditure	239.053	209.154	0.00	1400.00
Food consumption expenditure	3273.651	3696.973	0.00	35197.00
Total consumption expenditure	3933.983	4508.567	5.00	62909.00
Time spent on food production	2.148	12.066	0.00	151.00
Food production	0.109	0.312	0.00	1.00
Climate smart garden	0.019	0.136	0.00	1.00
Sex of household head	0.275	0.447	0.00	1.00
Age of household head	42.741	12.362	19.00	84.00
Education level of household head	0.313	0.464	0.00	1.00
Employment status of household head	0.736	0.441	0.00	1.00
Household size	3.706	1.895	1.00	12.00

Access to electricity	0.972	0.164	0.00	1.00
Permanent wall	0.323	0.468	0.00	1.00
Access to flush toilet	0.287	0.453	0.00	1.00
Co-operative society membership	0.312	0.464	0.00	1.00
No. of households	901			

Note: Food insecurity experience scale is the sum of 10 items taking ‘1’ if answer is ‘yes’ and ‘0’ otherwise that measure whether there was a time in the last 30 days when the respondent or any other adult in the household, due to a lack of money or other resources: (1) worried they would run out of food, (2) were unable to eat healthy and nutritious/preferred foods, (3) ate only a few kinds of foods, (4) had to skip a meal, (5) ate less than they thought they should, (6) ran out of food, (7) were hungry but did not eat, (8) went without eating for a whole day, (9) restricted consumption in order for children to eat, or (10) borrowed food or relied on help from a friend or relative. Food insecurity incidence is a dummy variable taking ‘1’ if a household faced a situation where it did not have enough food in the past 12 months and ‘0’ otherwise. Household dietary diversity (HDD) is measured using a dummy variable taking ‘1’ if the number of food groups consumed by a household is greater than 8—the mean household dietary diversity score—out of 12 food groups seven days before the survey and ‘0’ otherwise. The food groups include: (1) cereals and cereal products, (2) starches, (3) sugar and sweets, (4) pulses, (5) nuts and seeds, (6) vegetables, (7) fruit, (8) meat, meat products, and fish, (9) milk and milk products, (10) oils and fats, (11) spices and other foods, and (12) beverages. Vegetable consumption expenditure includes the weekly amount in Kenyan Shillings spent on spinach, cabbage, and other green vegetables. Food consumption expenditure is measured as the weekly amount in Kenyan Shillings spent on food eaten within and outside of the household. Total consumption expenditure is measured as the weekly amount in Kenyan Shillings spent on food eaten both within and outside of the household and on non-food goods and services. Time spent on food production is measured as the number of days spent watering and weeding crops grown at the household’s dwelling place. Food production is measured using a dummy variable taking ‘1’ if the household grows any crops at its dwelling place and ‘0’ otherwise. Climate smart garden (CSG) is a dummy variable taking ‘1’ if the household grows crops using a vertical garden and ‘0’ otherwise. Sex of household head is a dummy variable taking ‘1’ if the household is headed by a female and ‘0’ otherwise. Age of the household head is measured in years. Education level of the household head is a dummy variable taking ‘1’ if the household head has post-primary education and ‘0’ if otherwise. Employment status of household head is a dummy variable taking ‘1’ if the household head works for pay and ‘0’ otherwise. Household size is the number of people who have lived in the household for at least six months, and for at least half of the week in each week of those months. Access to electricity is a dummy variable taking ‘1’ if electricity is the major fuel used for lighting by a household and ‘0’ otherwise. Permanent wall is a dummy variable taking ‘1’ if the walls of the household’s main dwelling are predominantly made of bricks, concrete, or cement, and ‘0’ otherwise. Access to flush toilet is a dummy variable taking ‘1’ if the household’s main toilet facility is a flush toilet and ‘0’ otherwise. Co-operative society membership is a dummy variable taking ‘1’ if any member of the household is a member of a credit or savings group and ‘0’ otherwise.

Table 1 provides the baseline summary statistics of the variables used in the study. At an average of 7.332 on a scale of 0-10, the FIES was relatively high, indicative of high levels of food and nutrition insecurity. Correspondingly, the food insecurity incidence was also high, with about 75% of the households reporting that they had faced a situation when they did not have enough food in the last 12 months. Only 37% of the households had a relatively high HDD, indicating that they had consumed more than 8 of the 12 food groups during the week before the survey. This suggests that most households had low dietary diversity. Based on weekly averages, households spent $1.59 (KES 239) on vegetables, $21.82 (KES 3,274) on food, and $26.23 (KES 3,934) on total consumption, with substantial variation across households. Households typically spent 2 days watering and weeding crops grown at home. In addition, about 11% of the households engaged in food production, with only about 2% using CSGs. With regards to household characteristics, about 28% of the households were headed by women, and the average age of a household head was 43 years. Notably, about 74% of the household heads had post-primary education, and 97% of the households used electricity as their major fuel for lighting. On average, a household included four people, while less than one-third of the households lived in a dwelling with a permanent wall, had access to a flush toilet, and had at least one household member of a co-operative society.

Table 2. Baseline balance: Effect of household characteristics on treatment assignment

	(1)	(2)
Outcome: Treatment assignment	Climate smart garden	Climate smart garden and frass fertilizer
Sex of household head	-0.026	-0.065
	(0.031)	(0.039)
Age of household head	-0.187	-0.554
	(1.073)	(1.241)
Education level of household head	-0.024	0.009
	(0.044)	(0.037)
Employment status of household head	-0.035	0.036
	(0.032)	(0.042)
Household size	-0.239	-0.018
	(0.231)	(0.197)
Access to electricity	0.006	0.029*
	(0.012)	(0.011)
Permanent wall	-0.024	0.000
	(0.055)	(0.052)
Access to flush toilet	0.054	0.062
	(0.057)	(0.045)
Co-operative society membership	-0.041	-0.027
	(0.057)	(0.039)
No. of households	329	287

Note. The outcome variable is the treatment assignment. The reference group that is omitted is the control group, which consists of 285 households. Each row is a regression of the baseline covariate listed in the variables column on the indicators for the different treatment groups. Column (1) represents the first treatment, climate smart garden (CSG). Column (2) represents the second treatment, CSG and frass fertilizer (BSFFF). Sex of household head is a dummy variable taking '1' if the household is headed by a female and '0' otherwise. Age of the household head is measured in years. Education level of the household head is a dummy variable taking '1' if the household head has post-primary education and '0' if otherwise. Employment status of household head is a dummy variable taking '1' if the household head works for pay and '0' otherwise. Household size is the number of people who have lived in the household at least six months, and at least half of the week in each week in those months. Access to electricity is a dummy variable taking '1' if electricity is the major fuel used for lighting by a household and '0' otherwise. Permanent wall is a dummy variable taking '1' if the walls of the household's main dwelling are predominantly made of bricks, concrete, or cement, and '0' otherwise. Access to flush toilet is a dummy variable taking '1' if the household's main toilet facility is a flush toilet and '0' otherwise. Co-operative society membership is a dummy variable taking '1' if anyone in the household is a member of a credit or savings group and '0' otherwise.
Standard errors in parentheses clustered at enumeration area.
*** p<.01, ** p<.05, * p<.1

Table 2 shows the baseline balance of household characteristics. Except for access to electricity, there were no statistically significant differences between the treatment groups and the control group.

Table 3. Summary statistics: Endline food production practices using climate smart gardens

Variable	Obs	Mean	Std. Dev.	Min	Max
Climate smart garden adoption	468	0.96	0.20	0.00	1.00
Days to harvest	448	34.42	21.81	0.00	90.00
Number of harvests	448	4.48	5.89	0.00	45.00
Crop fully harvested	448	0.18	0.38	0.00	1.00
Unharvested crop (%)	448	48.25	28.31	0.00	100.00
Quantity of crop harvested (kg)	357	5.71	10.36	0.00	50.00

Value of crop harvested (KES)	357	325.87	580.66	0.00	5000.00
Quantity of harvest consumed (kg)	357	5.12	9.53	0.00	50.00
Value of harvest consumed (KES)	357	316.65	524.25	0.00	3000.00
Sale of harvest	448	0.02	0.14	0.00	1.00
Quantity of harvest sold (kg)	9	2.44	1.81	1.00	6.00
Value of harvest sold (KES)	9	126.67	66.90	50.00	240.00
Harvest given away	448	0.31	0.461	0.00	1.00
Crop affected by pests	448	0.37	0.48	0.00	1.00
Crop affected by disease	448	0.27	0.45	0.00	1.00
Crop affected by weeds	448	0.16	0.37	0.00	1.00
Post-harvest loss	448	0.44	0.50	0.00	1.00
Value of post-harvest loss (KES)	196	179.85	196.62	0.00	1000.00
Climate smart garden in poor condition	448	0.15	0.36	0.00	1.00
Climate smart garden in fair condition	448	0.23	0.42	0.00	1.00
Climate smart garden in good condition	448	0.61	0.49	0.00	1.00
Vegetables in poor condition	448	0.20	0.40	0.00	1.00
Vegetables in fair condition	448	0.27	0.44	0.00	1.00
Vegetables in good condition	448	0.53	0.50	0.00	1.00
Climate smart garden protected	448	0.39	0.49	0.00	1.00
Additional crops grown	448	0.15	0.35	0.00	1.00
Crop caregiver, household head	448	0.48	0.50	0.00	1.00
Crop irrigated	448	0.90	0.29	0.00	1.00
Bucket or watering can	405	0.84	0.36	0.00	1.00
Piped water	405	0.36	0.48	0.00	1.00
Daily waterings	405	0.62	0.48	0.00	1.00
Daily water use (litres)	405	18.36	10.17	0.00	40.00
Purchased water	405	0.86	0.34	0.00	1.00
Water cost (KES)	350	239.24	601.81	0.00	4800.00
Lack of water	448	0.31	0.46	0.00	1.00
Water support	448	0.45	0.50	0.00	1.00
Fertilizer support	448	0.39	0.49	0.00	1.00

Note. Climate-smart garden (CSG) adoption was measured as a dummy variable equal to 1 if the household owned a CSG and 0 otherwise. Days to harvest captured the number of days from planting to the first harvest, while the number of harvests indicates the total harvests obtained during the study period. Crop fully harvested was a dummy variable equal to 1 if the crop was fully harvested and 0 otherwise, and unharvested crop (%) measured the percentage of the crop left unharvested at the end of the study. Quantity of crop harvested (kg) and its value (in Kenyan Shillings) captured the total weight and estimated market value of harvested vegetables, whereas quantity and value of harvest consumed measured the amount and estimated the value consumed by the household. Sale of harvest was a dummy variable equal to 1 if any portion was sold and 0 otherwise, with quantity and value of harvest sold measuring the amount sold in kilograms and in Kenyan Shillings, respectively. Harvest given away was coded 1 if any harvest was given away and 0 otherwise. Crop damage variables—pests, disease, and weeds—were coded as dummy variables equal to 1 if crops were affected and 0 otherwise, and post-harvest loss captured losses similarly, with an estimated value in Kenyan Shillings. The condition of the CSG and vegetables was recorded using dummy variables for poor, fair, or good condition, equal to 1 if applicable and 0 otherwise. Climate smart garden protected was coded 1 if protective measures such as nets and other materials were used and 0 otherwise. Additional crops grown was a dummy variable taking 1 if a household grew vegetables other than those provided by the project and 0 otherwise. Crop caregiver was a dummy variable taking 1 if the main caregiver was the household head and 0 otherwise. Irrigation practices were captured through crop irrigated (1 if irrigated, 0 otherwise), use of buckets or watering cans (1 if buckets or watering cans were used for irrigation, 0 otherwise), and piped water availability (1 if source of water was piped, 0 otherwise). Daily waterings were coded 1 if watering occurred at least twice daily and 0 otherwise, and daily water use was measured in liters applied per day. Purchased water was coded 1 if water was bought and 0 otherwise, with the water cost recorded in Kenyan Shillings. Finally, household-reported challenges and support needs were captured through dummy variables for lack of water, water support, and fertilizer support, all coded 1 if applicable and 0 otherwise.

Table 3 provides summary statistics on urban agriculture practices from the endline survey. As expected, the adoption of CSGs was very high (95%). Crops matured relatively quickly, with an average of 34 days (5 weeks) to harvest. However, only 18% of crops were fully harvested, while nearly half of the crop (48%) remained unharvested on average. Harvest quantities and values were highly variable. The average harvested quantity was 5.7 kg, valued at about $2 (KES 326), which was in line with the prescribed CSG production. Most of the harvest was consumed at home. Market participation was minimal, with only 2% of households reporting the sale of harvests. Sales data was based on very few observations, suggesting that production was largely focused on subsistence rather than commercial purposes.

Table 3 also shows that about 31% of the households gave away their produce. Production challenges were notable, with about 37% of crops affected by pests, 27% by disease, and 16% by weeds. About 44% of the households experienced post-harvest loss, with an average value of about $1 (KES 180). Most of the CSGs (61%) and vegetables (53%) were in good condition (see Figure 3 depicting the different physical conditions of CSGs and vegetables). About 39% of the households used nets and other materials to protect the CSGs. About 15% of the households grew indigenous vegetables and other vegetables such as onions in addition to those provided by the project. The head of the household was the main caregiver for the crops in about half of the households (48%).

Figure 3 about here

Substantial dependence on irrigation was observed. About 90% of crops were irrigated, suggesting that crop production largely depended on supplemental water. About 84% of the participating households used buckets or watering cans, highlighting a strong dependence on manual irrigation methods. About 36% had access to piped water, suggesting that more reliable or fixed water infrastructure was available to only about one-third of households. Most households (64%) relied on boreholes, wells, ponds, tanks, and rivers or streams (Table 3).

Table 3 shows that watering practices were generally frequent, with about 62% of households watering their crops at least twice daily. Average daily water use was approximately 18 litres, with considerable variation (standard deviation = 10.2 litres) within a range of 0 to 40 litres per day, reflecting large differences in water access. Widespread reliance on purchased water was recorded, with 86% of irrigating households buying water, leaving only 14% reliant on free or self-owned water sources. The average daily water cost was $1.6 (KES 239), however costs varied substantially, with some households paying nothing and others spending up to $32 (KES 4,800). This wide range indicates significant inequality in water expenditure, suggesting that irrigation costs may be a major constraint for some households and could affect water use intensity, crop outcomes, and ultimately food security and nutrition. About one-third of the households identified water scarcity as a major challenge in managing the CSGs. Finally, the households indicated that support with water (45%) and fertilizer (39%) would be beneficial.

4. Empirical strategy

This study identified the impact of urban agriculture using random assignment of clusters into the treatment and control conditions. Random assignment enabled us to obtain unbiased average effects of CSG and BSFFF. This study used the ordinary least squares (OLS) estimator including post-treatment data to estimate the effects as follows:

$$Y_i = \alpha_i + \beta_1 CSG_i + \beta_2 CSG\&BSFFF_i + \epsilon_i \tag{2}$$

where Y_i represents household food and nutrition security outcomes comprising FIES, food insecurity incidence, HDD, and household welfare including vegetable consumption expenditure, food consumption expenditure, total consumption expenditure, food production, and time spent on food production for household i. CSG_i represents a dummy variable with a value of 1 for households assigned to receive CSGs and 0 otherwise. $CSG\&BSFFF_i$ is a dummy variable with a value of 1 for households assigned to receive CSGs and BSFFF and 0 otherwise. α_i represents the constant, β_1 captures the average treatment effect of CSGs (Treatment 1), and β_2 captures the average treatment effect of CSGs and BSFFF (Treatment 2). ϵ_i represents the error term.

Randomization was conducted at the cluster level using EAs. Households in the same EA are likely to be exposed to a similar socio-economic environment, which can result in the correlation of unobserved effects across households from the same EA. Following standard practice, we clustered standard errors at the EA level, which was the level of treatment (Abadie et al., 2023).

While the study implemented equal assignment to the two treatments and the control group, noncompliance with treatment assignment was not completely ruled out. Hence, β_1 and $\beta_2$are interpreted as estimates of the intention to treat, i.e., the impact of offering CSGs and BSFFF, rather than the actual impact for those who complied with the assigned treatment. While the intention to treat analysis can underestimate the true treatment effect due to noncompliance, it provides a more realistic estimate of the treatment effects in a real-world setting where noncompliance is common. This parameter sheds light on the potential impact of offering CSGs and BSFFF to households, including those who do not ultimately use them.

To approximate the treatment effects in percentage terms when the dependent variables are in levels, we divide the estimated coefficient by the mean of the dependent variable in the control group. We approximate treatment effects using marginal effects (ME) for binary outcomes. For dependent variables in natural logarithmic form, the estimated coefficients reflect multiplicative effects and indicate the percentage change in the outcome.

5. Results and discussion

Out of 901 households at baseline, 91 were lost to follow-up at the endline, resulting in an attrition of about 10%. The attrition was comprised of 29 households from the control group, 34 households from the CSG only treatment, and 28 households from the CSG and BSFFF. Attrition occurred for several reasons, including household migration, death, inability to participate in the endline survey due to work or travel commitments, and refusal to participate following theft or destruction of the CSGs, among other factors. We tested for differential attrition by regressing an attrition indicator on treatment assignment and baseline covariates including FIES using clustered standard errors. We found no evidence that attrition was correlated with treatment status or the baseline food and nutrition insecurity. Treatment coefficients were small and statistically nonsignificant, and a joint F-test failed to reject the null of no relationship ($\rho = 0.99$). These results suggest that attrition was unlikely to bias our estimates.

Table 4. Impact of urban agriculture on food and nutrition security

Outcome:	Food insecurity experience scale			Food insecurity incidence						Household dietary diversity					
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
	OLS	OLS	OLS	Probit	ME	Probit	ME	Probit	ME	Probit	ME	Probit	ME	Probit	ME
	Full	Women	Men	Full	Full	Women	Women	Men	Men	Full	Full	Women	Women	Men	Men
Climate smart garden only	-0.882**	-1.182**	-0.741*	-0.326**	-0.077**	-0.465**	-0.099**	-0.276*	-0.066*	0.189**	0.064**	0.235	0.071	0.187	0.065
	(0.351)	(0.451)	(0.386)	(0.153)	(0.034)	(0.227)	(0.044)	(0.168)	(0.040)	(0.089)	(0.030)	(0.157)	(0.046)	(0.116)	(0.040)
Climate smart garden and frass fertilizer	-0.884**	-1.505**	-0.663*	-0.378**	-0.089**	-0.344	-0.074	-0.376*	-0.090*	0.163	0.055	-0.143	-0.044	0.250*	0.086*
	(0.338)	(0.586)	(0.357)	(0.173)	(0.040)	(0.313)	(0.067)	(0.211)	(0.052)	(0.134)	(0.046)	(0.144)	(0.045)	(0.143)	(0.051)
Observations	810	220	590	810	810	220	220	590	590	810	810	220	220	590	590
Mean dependent variable, control group	7.848	8.051	7.757	0.891		0.899		0.887		0.313		0.316		0.311	
R2 / Pseudo-R2	0.088	0.150	0.078	0.044		0.122		0.031		0.086		0.150		0.078	

Note: The treatments include climate smart garden (CSG) only (Treatment 1) and CSG and frass fertilizer (BSFFF) (Treatment 2). Food insecurity experience scale is the sum of 10 items taking '1' if answer is 'yes' and '0' otherwise, measuring whether there was a time in the last 30 days when the respondent or any other adult in the household, due to a lack of money or other resources: (1) worried they would run out of food, (2) were unable to eat healthy and nutritious/preferred foods, (3) ate only a few kinds of foods, (4) had to skip a meal, (5) ate less than they thought they should, (6) ran out of food, (7) were hungry but did not eat, (8) went without eating for a whole day, (9) restricted consumption in order for children to eat, or (10) borrowed food or relied on help from a friend or relative. Food insecurity incidence is a dummy variable taking '1' if a household faced a situation where it did not have enough food in the past 12 months and '0' otherwise. Household dietary diversity (HDD) is measured using a dummy variable taking '1' if the number of food groups consumed by a household is greater than 8—the mean household dietary diversity score—out of 12 food groups seven days before the survey and '0' otherwise. The food groups include: (1) cereals and cereal products, (2) starches, (3) sugar and sweets, (4) pulses, (5) nuts and seeds, (6) vegetables, (7) fruit, (8) meat, meat products, and fish, (9) milk and milk products, (10) oils and fats, (11) spices and other foods, and (12) beverages. All models include baseline outcomes.
Standard errors are in parentheses and clustered at the enumeration area level.
* p<0.10, ** p<0.05, *** p<0.01

Table 5. Impact of urban agriculture on household consumption expenditure

Outcome:	Ln Vegetable consumption expenditure			Ln Food consumption expenditure			Ln Total household consumption expenditure		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	OLS	OLS	OLS	OLS	OLS	OLS	OLS	OLS	OLS
Climate smart garden only	-0.713**	-1.517**	-0.368	-0.032	-0.010	-0.040	0.052	0.058	0.053
	(0.294)	(0.567)	(0.306)	(0.100)	(0.199)	(0.126)	(0.072)	(0.126)	(0.100)
Climate smart garden and frass fertilizer	-0.956***	-1.456**	-0.737**	0.078	0.097	0.061	0.027	0.031	0.026
	(0.270)	(0.551)	(0.276)	(0.113)	(0.195)	(0.133)	(0.090)	(0.117)	(0.124)
Observations	810	220	590	810	220	590	810	220	590
Mean dependent variable, control group	4.102	4.509	3.921	7.456	7.317	7.518	7.706	2841.380	7.743
R-squared	0.132	0.156	0.138	0.056	0.070	0.065	0.098	0.122	0.095

Note. The treatments include climate smart garden (CSG) only (Treatment 1) and CSG and frass fertilizer (BSFFF) (Treatment 2). All expenditure measures are expressed in natural logarithms. Vegetable consumption expenditure includes the weekly amount in Kenyan Shillings spent on spinach, cabbage, and other green vegetables. Food consumption expenditure is measured as the weekly amount in Kenyan Shillings spent on food eaten both within and outside of the household. Total consumption expenditure is measured as the weekly amount in Kenyan Shillings spent on food eaten both within and outside of the household and non-food goods and services. All models include baseline outcomes.
Standard errors are in parenthesis and clustered at the enumeration area level.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 6. Impact of urban agriculture on food production

Outcome:	Household food production						Time spent on food production		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Probit	ME	Probit Women	ME	Probit	ME	OLS	OLS	OLS
Climate smart garden only	1.611***	0.458***	1.405***	0.415***	1.696***	0.472***	22.351***	26.970***	20.678***
	(0.146)	(0.026)	(0.228)	(0.048)	(0.136)	(0.024)	(4.139)	(7.162)	(3.592)
Climate smart garden and frass fertilizer	1.814***	0.516***	1.809***	0.534***	1.819***	0.507***	22.011***	21.624***	22.226***
	(0.125)	(0.025)	(0.217)	(0.046)	(0.114)	(0.023)	(3.081)	(5.744)	(3.656)
Observations	810	810	220	220	590	590	810	220	590
Mean dependent variable, control group	0.168		0.177		0.164		4.129	5.722	3.418
R2 / Pseudo-R2	0.256		0.243		0.263		0.164	0.155	0.175

Note. The treatments include climate smart garden (CSG) only (Treatment 1) and CSG and frass fertilizer (BSFFF) (Treatment 2). Household food production is measured using a dummy variable taking 1 if the household grows any crops at its dwelling place and 0 otherwise. Time spent on food production is measured as the number of days spent watering and weeding crops grown at the household's dwelling place. All models include baseline outcomes.
Standard errors are clustered at the enumeration area level.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 4 shows the results of estimating the impact of CSGs and BSFFF on food and nutrition security outcomes. We found that both treatments had a positive impact on food and nutrition security. Specifically, CSGs only (Treatment 1) and CSGs and BSFFF (Treatment 2) reduced the FIES by about 11% and the incidence of food insecurity by about 8% and 9%, respectively. We observed that the CSGs and BSFFF (Treatment 2) had a larger impact on FIES and the food insecurity incidence than CSGs only (Treatment 1). In support of these findings, empirical studies in the context of urban locations in Kenya demonstrate that urban agriculture is positively correlated with food security (Gallaher et al., 2013; Omondi et al., 2017) and sustainable food production using organic waste (Lal, 2020; Menyuka et al., 2020). However, Averbeke (2007) finds that urban agriculture including home gardening has a modest impact on food security in the context of South Africa. Notwithstanding these results, our findings support the role of BSFFF in enhancing food security (Anyega et al., 2021; Awad et al., 2024; Beesigamukama et al., 2020; Tambeayuk et al., 2024; Tanga et al., 2022; Terfa, 2021).

In addition, we found that CSGs only (Treatment 1) had a positive impact on HDD, which increased by 6% (Table 4). This finding is similar to that of Swanepoel, Van Niekerk, and Tirivanhu (2021), who found that urban agriculture based on small backyard gardens increases dietary diversity. An increase in HDD is associated with household food and nutrition security and welfare (Ali et al., 2019; Garbero & Jäckering, 2021; Vandevijvere et al., 2010).

Table 4 provides results showing gendered differences in the effects of the interventions, given that women are central actors in providing and producing food in the household. Overall, we found that both treatments had a negative impact on FIES and food insecurity incidence for both women and men, but with a greater impact for female-headed households. The CSGs (Treatment 1) reduced the FIES by 15% for female-headed households and by 10% for their male-headed counterparts, respectively. The CSGs and BSFFF (Treatment 2) reduced the FIES by 19% and 9% for female-headed and male-headed households, respectively. Similarly, the CSGs only (Treatment 1) reduced the food insecurity incidence by 10% and 7% for female-headed households and their male counterparts, respectively. However, CSGs and BSFFF (Treatment 2) reduced food insecurity incidence by 9% for male-headed households only. Similarly, CSGs and BSFFF (Treatment 2) increased HDD by 9% for male-headed households only.

Table 5 shows that both treatments including CSGs only (Treatment 1) and CSGs and BSFFF (Treatment 2) reduced vegetable consumption expenditure for the full sample by 51% and 62%, respectively. We also observe gendered impacts, with CSGs only (Treatment 1) reducing vegetable consumption expenditure by 78% for female-headed households only. However, CSGs and BSFFF (Treatment 2) reduces vegetable consumption expenditure for both women and men, but with a much larger magnitude for female-headed households (77% vs. 52%). These results indicate that participation in urban agriculture substantially reduced household spending on vegetables, which is consistent with increased self-production and home consumption replacing market purchases. The effects were particularly large and robust among female-headed households. Notwithstanding these results, we did not observe any meaningful effect of the treatments on food consumption expenditure and total household consumption expenditure (c.f. Swanepoel et al., 2021; Averbeke, 2007). The reductions in vegetable spending did not translate into statistically significant changes in food or total household consumption expenditure, suggesting budget reallocation rather than income effects.

Urban agriculture including home gardens increases access to fresh produce and often to culturally appropriate food, especially in areas where such produce is expensive or limited. Kiribou et al. (2024) argue that urban agriculture promotes food affordability and fosters food supply systems, food and nutrition security, jobs and income generation, and the reduction of transportation costs. By growing their own food, households can reduce their reliance on expensive, long-distance food supply chains.

Furthermore, Gunapala et al. (2025) claim that technological advancements are imperative for overcoming impediments to urban agriculture, and can promote biodiversity and resilience. In particular, the convergence of innovative technology and farming practices, including intensive and technologically advanced production techniques such as vertical gardening including CSGs and BSFFF, can maximize food production (Gamage et al., 2024).

Compared to traditional farming practices and intensive industrial agriculture, sustainable agriculture including innovative urban agriculture technologies can preserve resources, benefitting both the natural environment and social welfare. Vertical gardens integrate greenery into high-density living spaces, thus promoting socio-economic and sustainable environments (Gamage et al., 2024; Gunapala et al., 2025; Lal, 2020).

The interventions were expected to increase the likelihood of food production and the time spent on food production at the dwelling place (Bisaga et al., 2019; Lal, 2020). Table 6 shows that CSGs only (Treatment 1) and CSGs and BSFFF (Treatment 2) increased the likelihood of food production by 46% and 52%, respectively, across the full sample. We observed gendered impacts, with CSGs only (Treatment 1) increasing the likelihood of food production by a smaller magnitude for women as compared to men (42% vs. 47%). However, CSGs and BSFFF (Treatment 2) increased the likelihood of food production for both women and men, with a slightly larger magnitude for women (53% vs 51%).

This study also finds that CSGs only (Treatment 1) and CSGs and BSFFF (Treatment 2) increased the time spent on food production fivefold (i.e., by slightly more than 22 days) for the full sample (Table 6). The CSGs only (Treatment 1) increased the time spent on food production in both samples but with a marked increase for female-headed households, which saw a fivefold increase of 27 days as compared to a fourfold increase of 21 days for their male counterparts. In contrast, CSGs and BSFFF (Treatment 2) increased the time spent on food production in both samples but with a somewhat larger increase for men, namely a sixfold increase of 22 days for women as compared to a sevenfold increase of 22 days for men. Nevertheless, we note that this measure was imprecise, as it records the number of days spent on weeding, watering, and harvesting rather than the actual duration of time, and households likely spent considerably less time than these counts suggest.

Vertical gardens at the dwelling place are practical and easy to access logistically. Urban dwellers in high-density informal settlements face challenges in terms of land tenure and access to services, which undermines food production and ultimately food and nutrition security (Bisaga et al., 2019). Living in close proximity to food production systems that use innovative production technologies and techniques that are amenable to short-term production in the face of insecure land tenure promotes agricultural production in urban settlements (Suchá & Dušková, 2022).

Taken together, we find evidence that urban agriculture may appeal to women logistically, and thus foster food production and ultimately food and nutrition security and household welfare. Urban farming is likely to be integrated with household responsibilities and require less time commitment and resources than traditional farming, and can potentially address issues of land tenure including accessing, using and controlling land in urban informal settlements (Bisaga et al., 2019; Blessing, 2019; Poulsen et al., 2015; Surya et al., 2020).

Based on the survey and input data from this study, the financial analysis of CSGs shows that each garden generated harvested vegetables with an average value of $28 (KES 4,200) over a four-month cycle (Table 7). The associated costs included the amortized installation cost of $2.50 (KES 375), fertilizer at $0.30 (KES 45), water at $6.40 (KES 960), labor for watering and maintenance at $12 (KES 1,800), and an estimated opportunity cost of land of $3 (KES 450), bringing total costs to approximately $24 (KES 3,600) per cycle. This results in a net benefit of $4 (KES 600) per cycle and a benefit-cost ratio of 1.15. Assuming three full production cycles per year, households could earn an annualized net benefit of $12 (KES 1,800). These figures suggest that CSGs provide both a source of food and a modest financial return, making them a viable and valuable investment for households in urban informal settlements.

Table 7. Benefit-cost analysis of climate smart gardens and frass fertilizer

Item	Amount ($)	Amount (KES)
Benefit		
Value of harvested vegetables	28.00	4200.00
Cost		
Installation of climate smart garden	2.50	375.00
Frass fertilizer	0.30	45.00
Water	6.40	960.00
Labor	12.00	1800.00
Opportunity cost of land	3.00	450.00
Total costs	(24.00)	(3600.00)
Net benefit per cycle	4.00	600.00
Benefit-cost ratio	1.17	1.17
Annualized net benefit	12.00	1800.00

Note. The values in this table are based on input data from the study. The calculations assume that each production cycle lasts four months, allowing for three full cycles per year. All benefits and costs are presented in both U.S. Dollars ($) and Kenyan Shillings (KES). Benefits include the value of harvested vegetables. Installation costs including $25 per climate smart garden (CSG) are amortized over its lifespan, which is about 10 years. Labor costs include watering, weeding, and general maintenance, while water costs assume a maximum of 20 liters per cycle, with seedlings watered twice daily initially and mature plants watered 2–3 times per week. Each CSG uses 2.5 - 3 kg of frass fertilizer (BSFFF) per cycle, sourced from certified producers that recycle organic and human waste. The opportunity cost of land reflects the value of the 1 m^2 area occupied by a CSG. Net benefit per cycle is calculated as the value of harvested vegetables minus total costs, and the benefit-cost ratio represents the ratio of total benefits to total costs per cycle. Annualized net benefit is based on three production cycles per year.

6. Conclusion

Households living in high-density informal settlements in urban cities typically grapple with food and nutrition insecurity, waste management, and sanitation. Urban agriculture, including sustainable food production, offers a pivotal solution for building resilient farming systems in such contexts.

This study used a cluster RCT to investigate the impact of urban agriculture including CSGs and BSFFF on food and nutrition security in urban informal settlements. As innovative farming technologies, CSGs take up little space and offer a practical intervention in high-density settlements, while BSFFF fosters waste management and sanitation. We found that urban agriculture improved food and nutrition security, household welfare, and food production. In addition, urban agriculture had a bigger effect on female-headed households.

This study implemented a circular economy approach encompassing socio-economic and environmental benefits. In the context of this study, the circular economy approach was associated with improvements in socio-economic outcomes including food and nutrition security, household welfare, and food production. The circular economy approach minimizes waste pollution through recycling human waste to produce BSFFF and thus offers environmental protection. Circular agriculture and nature-based solutions improve crop yield and help to restore degraded ecosystems and foster urban greening.

To ensure that innovative farming technologies such as CSGs and BSFFF are accessible and affordable, policies supporting a circular economy in informal settlements are imperative for promoting food and nutrition security, household welfare, and sustainable waste management. Poverty reduction policies can include urban agriculture initiatives targeting poor households in informal settlements. Similarly, sustainable waste management policies can benefit urban agriculture by promoting the use of organic fertilizer from recycled household waste. In addition, public-private partnerships can also facilitate technology transfer and training to foster the effective use of innovative farming technologies. Policies integrating land use management in urban informal settlements can improve land access and infrastructure, which can in turn maximize the potential for urban agriculture in poor urban settings. Lastly, the recommended policies should integrate gender mainstreaming to foster gender equality and economic empowerment for women.

Urban agriculture in informal settlements promotes food and nutrition security, household welfare and resilience, and waste management and sanitation. Urban agriculture therefore contributes towards the achievement of several SDGs, including SDG 1- no poverty, SDG 2 - zero hunger, SDG 3 - good health and well-being, SDG 5 - gender equality, SDG 6 - clean water and sanitation, SDG 11 - sustainable cities and communities, SDG 12 - responsible consumption and production, and SDG 13 - climate action. However, the impact of urban agriculture on overall food security and production is limited by persistent challenges that impede agricultural production in urban informal settlements, including poor urban planning, land tenure rights, and waste management.

While this study offers valuable insights into the impact of urban agriculture on households, this topic remains understudied in the context of sub-Saharan Africa, where a high proportion of the urban population live in food and nutrition insecure conditions. Moreover, there is limited research on the effect of waste management interventions on urban agriculture and food and nutrition security. Furthermore, studies that critically evaluate gender differences in the adoption of urban agriculture, including emerging innovative production technologies and techniques and in particular BSFFF, are lacking. Therefore, further research is needed to evaluate such interventions and generate deeper insights that can inform policies surrounding food and nutrition security in the region.

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Ethical approval

This study was approved by the Unites States International University - Africa Ethics Review Committee (Approval No. USIU-A/IRB/142-2023).

Study pre-registration

AEA RCT Registry no. AEARCTR-0011089 at https://www.socialscienceregistry.org/trials/11089

Data availability

The data that support the findings of this study are available from the author, upon reasonable request.

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Figure 3. Physical condition of climate smart gardens and vegetables

Panel A: Climate smart garden and vegetables in good condition

Panel B: Climate smart garden in fair condition

Panel C: Climate smart garden and vegetables in poor condition

Panel D: Damaged climate smart garden