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Eco-Efficiency Assessment and Food Security Potential of Home Gardening: A Case Study in Padua, Italy

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Abstract: In the expanding urban agriculture phenomenon in Europe, home gardens are a traditional form that have kept agriculture within cities, even becoming crucial in certain historical periods (e.g., war periods). However, horticultural practices in home gardens can also have negative consequences. The goal of this paper is to assess the eco-efficiency of home gardens as a type of urban agriculture. To do so, a case study in Padua (Italy) was evaluated following life cycle assessment and life cycle costing methods. A home garden of 30.6 m² and 21 crop cycles were evaluated. The functional unit of the assessment was 1 kg of harvested fresh vegetable at the consumption point, and the ReCiPe method was employed for impact assessment. Environmental assessment indicated that organic fertilization, use of tap water, mineral fertilization and pesticides were the most contributing elements of the entire life cycle. Furthermore, the relevance of garden design and crop selection was a determinant in the eco-efficiency results. The assessed home garden could satisfy the food requirements of between 1 and 2 members of the household. Crop management and design recommendations are provided to improve eco-efficiency and food security potential of home gardens.

Keywords: urban agriculture; environmental impact assessment; local food production; life cycle assessment; urban food systems; sustainability; industrial ecology; food sovereignty; economic assessment; life cycle costing

1. Introduction

Vegetable production in cities has become a relevant topic as a result of urbanization and concentration of world population in urban areas [1], which place stress on both urban food security and environmental quality [2]. This demographic pressure has not only resulted in an urban sprawl that has negatively affected the environment—by impacting arable land, water, energy, biological resources [3], and waste generation [4]—but has also increased dependency on external sources of food [5]. Urban food demand has been satisfied by the development of conventional food systems that are based on industrialized and global supply-chains associated to environmental stresses [6]. Achieving sustainable food systems requires a renovation that promotes “in loco” [7] and environmentally-just [6] food production and consumption, and cities have become key spaces to integrate green and edible vegetation [8] for this purpose. Although urban agriculture (UA) literature

has proliferated, the quantification of the contribution of UA to sustainability is recent and still under discussion.

1.1. A Renewed Urban Agriculture

UA typologies (such as backyard gardens) have always been present in cities but the recent global economic crisis of 2008 brought back agriculture into cities in a wide and diverse manner. The increase of “food deserts” [9] and financial limitations of certain groups in the society has promoted the creation of urban gardens to tackle food insecurity [10,11], as already performed during war periods [12]. The emergence of UA, such as community gardens, was essential to cope with urban social injustices, which were accentuated during crisis times. It helped build communities and empower the society, as well as regenerate abandoned and degraded spaces [13–18], such as in shrinking cities [19,20] and post-disaster resilience [21]. In particular, UA also had a key role in the food justice movement [22] that aimed at tackling the disconnection between food production and consumption, and food and culture. Reynolds and Cohen [23] described the food justice dynamics and the role of UA in New York City, where unequal access to food and resources was often rooted in race and class differences. Such developments resulted in the sprout of a multifunctional and versatile UA within the context of the boosting of a renewed local food sector as an alternative food system [24].

This renovated UA has not only gained the attention of architects and urban planners, but also new entrepreneurs and innovators. UA designs currently include and integrate elements from the 19th century Howard’s ‘garden city’ concept [25] into high-technology and resource-efficient production techniques [26–28]. Marginal spaces in urban periphery have been replaced by vacant spaces as locations for UA in the urban fabric—such as rooftops, walls or buildings—by employing vertical and indoor farming systems [29,30]. Although the opportunities offered by urban food businesses are pushing for an entrepreneurial UA [31], urban farms might engage city-adjusted strategies in order to be more successful [32].

As a result of this process, multiple definitions of UA have proliferated, although the primary function of producing food—mainly crops and livestock—has remained as a framework notion [33]. Furthermore, the production of non-food products has been also included as part of the provisionary functions of UA [34,35]. Sanyé-Mengual [36] evaluated available definitions and identified four main variable aspects: space, production, function, and market. Within COST Action Urban Agriculture Europe [37], scholars made an effort to propose a comprehensive definition of UA:

“farming operations taking place in and around the city that beyond food production provides environmental services (soil, water, and climate protection; resource efficiency; biodiversity), social services (social inclusion, education, health, leisure, cultural heritage), and supports local economies by a significant direct urban market orientation” [38].

1.2. Home Gardens

Among the diverse UA methods, home gardens have expanded via private spaces that have turned into productive land, contributing to individual, household, and community food security [39] (i.e., the condition in which “all community residents obtain a safe, culturally acceptable, nutritionally adequate diet through a sustainable food system that maximizes community self-reliance and social justice” (p. 37) [40]). In particular, home gardens in the Global North have been crucial in specific historical events (e.g., wars and economic depressions) [12] and are a permanent form of agriculture in cities, increasing the vegetable and fruit uptake of the urban population quantitatively and qualitatively [41]. In fact, the total urban area devoted to private UA can be larger than the public UA area, such as for Chicago (United States) [42] or Rome (Italy) [43]. Taylor and Lovell [44] defined a home garden as a “garden managed by a single household on owned, rented or borrowed land, either on the same property as the residence or on adjacent land such as vacant lot, tree lawn or right of way (p. 2)”.

Research on home gardens has focused on seven main aspects: food security and access, resistance and empowerment, community development, social and cultural reproduction, biodiversity and ecological properties, agrobiodiversity and resilience [45]. Kortright and Wakefield [39] developed a home garden type, based on the five main motivations for gardeners: cook's gardens, teaching gardens, environmental gardens, hobby gardens and aesthetics gardens. This study also highlighted the contribution of home gardens to food security and accessibility, health and nutrition, and well-being. Taylor and Lovell [44] evaluated home gardens in households with different cultural backgrounds in Chicago (United States), demonstrating the positive role of home gardens in food security (both at household and community levels), in culturally acceptable foods' accessibility and in urban agrobiodiversity.

On the contrary, horticultural practices in home gardens can also have negative consequences, such as dependence on external inputs (e.g., chemicals, water, energy) and the negative impacts of their use [39]. In this line, a study on home gardens in Australia assessed the variables affecting water consumption in gardens, underlining the role of lifestyle and garden management practices [46]. However, no study have quantified the environmental impacts of urban food production in home gardens—thereby considering all the external inputs and the resulting productivity, unlike other typologies of UA (e.g., rooftop agriculture, community gardening, aquaponics) [47–55].

1.3. Goal and Objectives

The goal of this paper was to assess the eco-efficiency and food security potential of home gardens as a type of urban agriculture. The specific objectives were to address the following research questions:

- What are the environmental burdens of home gardens?
- What is the economic balance of vegetables production in home gardens?
- How can garden design and management promote eco-efficiency?
- How does a home garden contribute to the food security of home gardeners?

To do so, a case study in Padua (Italy) has been assessed, employing life cycle assessment (LCA) and life cycle costing (LCC) methods.

2. Materials and Methods

2.1. Case Study

The case study was a home garden located in Padua, Italy (Figure 1a). The garden had a total surface of 30.6 m² divided into different plots that accounted for a total productive area of 25 m²: nine parcels of 2 × 1 m, and two of 3.5 × 1 m (Figure 1b). In the home garden, 11 different vegetables were produced in 21 crop cycles (Figure 1c), including both leafy and fruit vegetables. Data was collected between 2012 and 2013, when cultivation was performed, including autumn-winter and spring-summer cycles varying from 51 to 216 days.

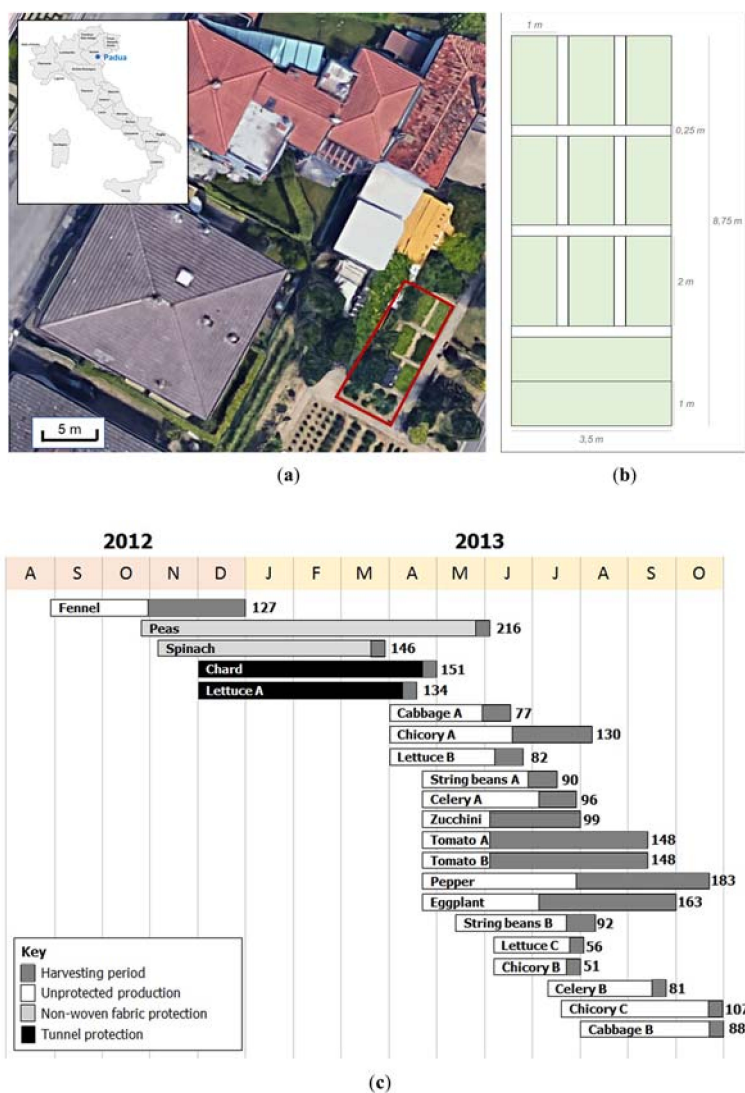


Figure 1. Case study specifications: (a) Location of Padua (Italy) and aerial image of the home garden (©Google Earth); (b) Design and dimensions of the garden and the plots; (c) Calendar of experimental crops, including crop cycle (days).

Regarding the agronomical characteristics of the garden (Table 1), soil cultivation was performed on the entire plot. The area devoted to each crop ranged from 0.5 m^2 to 4 m^2 . Irrigation was done with tap water, using a dripline irrigation system ($10 \text{ drippers} \cdot \text{m}^{-2}$) and manually, thereby excluding any electronic device as auxiliary equipment (e.g., timer, pump). Irrigation rate depended on the crop cycle and the amount of cold days (T_c) ($5 \text{ L} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$) and warm days (T_w) ($7 \text{ L} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$). Pest control treatments were performed only once per crop a few days after transplanting using 25 L of copper oxychloride at a concentration rate of $3.5 \text{ g} \cdot \text{L}^{-1}$. No energy consumption was required during the crop production, as the operations were performed manually. The vegetables were harvested for the gardener's self-consumption. Some agronomic practices were done homogeneously in the garden, while others depended on the crop (Table 1):

- Soil preparation (SP): Soil was manually dug and aerated as preparation for the crops.
- Protected crops (PC): Autumn-winter cycles of peas, spinach, chard and lettuces were protected with non-woven fabric. While only seedlings were protected for peas, tunnels were installed for the rest of the crops.

- Seeding (S) and Transplanting (TP): Commercial seeds or seedlings were used in the garden, depending on the crop and variety.
- Organic fertilization (OF): During soil preparation, plant nutrition was provided to all the crops homogeneously with initial fertilization of industrial compost (dosage of $1 \text{ kg}\cdot\text{m}^{-2}$).
- Mineral fertilization (MF): Fertilization was completed with a mineral fertilization with NPK (6-12-24) (dosage of $75 \text{ g}\cdot\text{m}^{-2}$) and ammonium nitrate (NH_4NO_3) (dosage of $25 \text{ g}\cdot\text{m}^{-2}$) for most of the crops.
- Crop rotation (CR): In two occasions, mineral fertilization was avoided as crops (i.e., lettuce, chicory) occurred after legumes (i.e., string beans) and nitrogen content was considered optimal.

Table 1. Specifications of the crops under assessment, including area (m^2), crop cycle (T, days)—differentiating between cold days (T_c) and warm days (T_w), yield ($\text{kg}\cdot\text{m}^{-2}$) and agronomic practices (soil preparation, SP; protected crop, PC; seeds, S; transplant of seedlings, TP; organic fertilization, OF; mineral fertilization, MF; and crop rotation, CR) (X indicates when a practice occurs).

Crop		Area (m^2)	Cycle (Days)			Yield ($\text{kg}\cdot\text{m}^{-2}$)	Agronomic Practices							
			T	T_c	T_w		SP	PC	S	TP	OF	MF	CR	
Fennel	<i>Foeniculum vulgare</i>	4	127	90	37	8.3	X				X (48)	X	X	
Peas	<i>Pisum sativum</i>	4	216	182	34	2.4	X	X	X(250 g)			X	X	
Spinach	<i>Spinacia oleracea</i>	1	146	146	0	3	X	X	X(20 g)			X		
Chard	<i>Beta vulgaris</i>	0.7	151	151	0	10	X	X		X (12)	X			
Lettuce "Cappuccia"	<i>Lactuca sativa</i>	1.3	134	134	0	3	X	X		X (12)	X			
Cabbage "Cappuccio"	<i>Brassica oleracea</i>	1	77	32	45	4.7	X			X (6)	X	X		
Chicory "Grumulo"	<i>Cichorium intybus</i>	1	130	32	98	7.7	X		X (1.5 g)		X	X		
Lettuce "Gentile"	<i>Lactuca sativa</i>	1	82	32	50	3.2	X			X (12)	X	X		
String bean	<i>Phaseolus vulgaris</i>	2	90	11	79	1.9	X		X (120 g)		X	X		
Zucchini	<i>Cucurbita pepo</i>	4	99	11	88	3.9	X			X (8)	X	X		
Celery	<i>Apium graveolens</i>	0.7	96	11	85	4	X			X (8)	X	X		
Tomato (bunch)	<i>Lycopersicon esculentum</i>	1	148	11	137	14.5	X			X (4)	X	X		
Tomato (table)	<i>Lycopersicon esculentum</i>	1	148	11	137	10.6	X			X (6)	X	X		
Pepper	<i>Capsicum annuum</i>	1.5	183	11	172	5.1	X			X (6)	X	X		
Eggplant	<i>Solanum melongena</i>	1	163	11	152	7.7	X			X (2)	X	X		
String bean	<i>Phaseolus vulgaris</i>	2	92	0	92	1.8	X		X (120 g)		X	X		
Lettuce "Cappuccia"	<i>Lactuca sativa</i>	1.2	56	0	56	2.9	X			X (12)	X		X	
Chicory "Catalogna"	<i>Cichorium intybus</i>	0.5	51	0	51	10.6	X			X (12)	X		X	
Celery	<i>Apium graveolens</i>	0.7	81	0	81	3.6	X			X (8)	X	X		
Chicory "Treviso" (Early)	<i>Cichorium intybus</i>	1.3	107	29	78	1.6	X			X (12)	X	X		
Savoy cabbage "Verza"	<i>Brassica oleracea</i>	2	88	27	61	5.0	X			X (12)	X	X		

2.2. Environmental and Economic Life Cycle Assessment

The environmental and economic performances of the home garden were evaluated from a life cycle perspective by applying Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) methods, respectively. The framework of LCA is regulated by the ISO 14040-14044 [56,57], which establishes a four-stage process: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation. LCC also follows a four-stage framework based on the same ISO, although life cycle impact assessment is substituted by “cost aggregation”, a step where the different costs of each life cycle stage are aggregated by category [58].

2.2.1. Goal and Scope

The purpose of the assessment was to quantify the environmental impacts and the economic cost of vegetables produced in home gardens. The functional unit of the assessment was 1 kg of harvested fresh vegetable at the consumption point. In this case, since the consumer was the gardener itself, the cradle-to-consumer approach can be considered as a cradle-to-fork one. The system boundaries, therefore, included all the stages of the life cycle of the vegetable from the extraction of raw materials to its consumption (Figure 2).

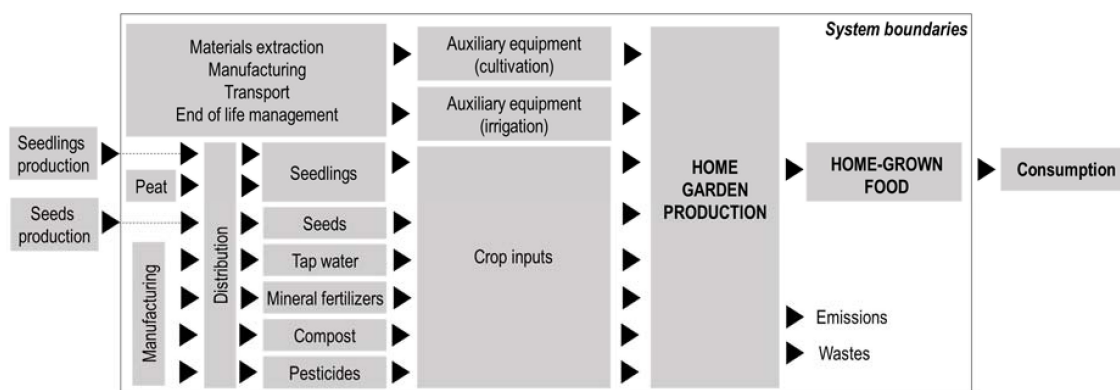


Figure 2. System boundaries and life cycle stages included in the life cycle assessment of vegetables production in home gardens.

2.2.2. Life Cycle Inventory

The life cycle inventory (LCI) for the crops under assessment was reported for the functional unit of 1 kg of harvested product (Table 2). The use of seeds, seedlings and fertilizers depended on the agricultural practices employed for each crop (as reported in Table 1).

Table 2. Life cycle inventory of home gardening for a functional unit of 1 kg of harvested food product. Amount depends on crop period (T)—including the number of cold days (T_c , between 01/10 and 30/04) and the number of warm days (T_w , between 01/05 and 30/09), and crop yield (J) (* Seeds, seedlings and fertilizers depend on the practices of each cycle, according to Table 1).

Element	Material	Amount	Unit	Transport		Waste Management	
				Distributor [Lorry]	Gardener [Car]	Treatment	Transport [Lorry]
Land occupation		$\frac{1 \text{ m}^2}{n \left[\frac{\text{kg}}{\text{m}^2} \right]} \times \frac{T \text{ [days]}}{365 \left[\frac{\text{days}}{\text{year}} \right]}$	m ² a	-	-	-	-
Nonwoven fabric	PP (100% virgin)	$\frac{0.03 \text{ kg}}{5 \text{ year}} \times \frac{1 \text{ m}^2}{n \left[\frac{\text{kg}}{\text{m}^2} \right]} \times \frac{T \text{ [days]}}{365 \left[\frac{\text{days}}{\text{year}} \right]}$	kg	-	-	-	-
Tunnel rods	Galvanized steel	$\frac{0.463 \text{ kg}}{15 \text{ year}} \times \frac{1 \text{ m}^2}{n \left[\frac{\text{kg}}{\text{m}^2} \right]} \times \frac{T \text{ [days]}}{365 \left[\frac{\text{days}}{\text{year}} \right]}$	kg	50 km	5 km	50% landfill 50% recycled	10 km
Plant net	PP (100% virgin)	$\frac{0.02 \text{ kg}}{5 \text{ year}} \times \frac{1 \text{ m}^2}{n \left[\frac{\text{kg}}{\text{m}^2} \right]} \times \frac{T \text{ [days]}}{365 \left[\frac{\text{days}}{\text{year}} \right]}$	kg	-	-	-	-
Tubes	HDPE	$\frac{0.141 \text{ kg}}{3 \text{ year}} \times \frac{1 \text{ m}^2}{n \left[\frac{\text{kg}}{\text{m}^2} \right]} \times \frac{T \text{ [days]}}{365 \left[\frac{\text{days}}{\text{year}} \right]}$	kg	50 km	5 km	-	-
Water	Tap water	$\left(5 \left[\frac{\text{L}}{\text{day}} \right] \times T_c \text{ [days]} + 7 \left[\frac{\text{L}}{\text{day}} \right] \times T_w \text{ [days]} \right) \times \frac{1 \text{ m}^2}{n \left[\frac{\text{kg}}{\text{m}^2} \right]}$	L	-	-	-	-
Seeds *	Seeds	$\frac{S \text{ (kg)}}{A \text{ (m}^2)} \times \frac{1 \text{ m}^2}{n \left[\frac{\text{kg}}{\text{m}^2} \right]}$	kg	215 km	5 km	-	-
Seedlings *	Peat (seedling substrate)	$0.02 \text{ kg} \times \frac{TP \text{ (t)}}{A \text{ (m}^2)} \times \frac{1 \text{ m}^2}{n \left[\frac{\text{kg}}{\text{m}^2} \right]}$	kg	50 km	5 km	-	-
Fertilizers *	Industrial compost	$\frac{1 \text{ kg}}{\text{m}^2} \times \frac{1 \text{ m}^2}{n \left[\frac{\text{kg}}{\text{m}^2} \right]}$	kg	50 km	20 km	-	-
	NPK 6-12-24	$\frac{0.075 \text{ kg}}{\text{m}^2} \times \frac{1 \text{ m}^2}{n \left[\frac{\text{kg}}{\text{m}^2} \right]}$	kg	50 km	5 km	-	-
	NH ₄ NO ₃	$\frac{0.025 \text{ kg}}{\text{m}^2} \times \frac{1 \text{ m}^2}{n \left[\frac{\text{kg}}{\text{m}^2} \right]}$	kg	50 km	5 km	-	-
	NH ₃ emission	$0.04 \times (N_{NPK} \text{ (kg)} + N_{NH_4NO_3} \text{ (kg)}) + 0.02 \times N_{compost} \text{ (kg)}$	kg	-	-	-	-
	N ₂ O emission	$0.0125 \times N_{total} \text{ (kg)}$	kg	-	-	-	-
	NO _x emission	$0.1 \times N - N_2O \text{ emission (kg)}$	kg	-	-	-	-
Pest management	Well water	$\frac{1 \text{ L}}{\text{m}^2} \times \frac{1 \text{ m}^2}{n \left[\frac{\text{kg}}{\text{m}^2} \right]}$	L	-	-	-	-
	Cu ₂ (OH) ₃ Cl	$\frac{0.0035 \text{ kg}}{\text{m}^2} \times \frac{1 \text{ m}^2}{n \left[\frac{\text{kg}}{\text{m}^2} \right]}$	kg	50 km	5 km	-	-

(a) Cultivation System and Auxiliary Equipment

This life cycle stage includes soil transformation and occupation, and the auxiliary equipment for cultivation and the irrigation system.

- Soil occupation: The implementation of the home garden implied the occupation of an unevenly built urban land for the entire crop period.
- Auxiliary equipment—Cultivation: Some winter crops required auxiliary equipment to protect them from adverse temperatures as well as a plant net to sustain proper growth. Peas and spinach were protected with non-woven fabric, which was raised above the ground with unused drawers to avoid growth hindrance. Lettuce and chard were grown in a tunnel made of non-woven fabric and supported by rods. The non-woven fabric was made of virgin polypropylene (density of $30 \text{ g}\cdot\text{m}^{-2}$) with lifespan of 5 years. The tunnel rods were made of galvanized steel, considering 95% recycled steel content. According to the design, the total amount of steel was of $463 \text{ g}\cdot\text{m}^{-2}$ (considering 3 rods per square metre—0.75 linear metre) with lifespan of 15 years. A plant net, which was employed to sustain the growth of climbing species (i.e., peas), was made of virgin polypropylene (density of $20 \text{ g}\cdot\text{m}^{-2}$) with a lifespan of 5 years. While the gardener obtained these products at a local store (5 km) and transported them in a private car, the production site was assumed as regional (50 km) and the distribution transport was considered to be performed with a 7.5 ton-lorry.
- Auxiliary equipment—Irrigation: The irrigation system included irrigation tubes that supply tap water from the house. The tubes were made of high-density polyethylene and were distributed in the garden at a ratio of $2 \text{ m}\cdot\text{m}^{-2}$. They weighed 70.5 g per linear meter and had a lifespan of 3 years. Distribution distance was considered for a regional supply (50 km) with a 7.5 ton-lorry. The gardener bought the irrigation materials at a store 20 km away.

(b) Crop Inputs

This life cycle stage includes all the resources required for crop cultivation.

- Seeds: While seeds production was excluded from the system boundaries following a mass cut-off criterion [59], transportation was included. The distribution distance was of 215 km, while the gardener acquired the seeds at the local market (5 km).
- Seedlings: The production of the seedlings was excluded due to lack of data and following a mass cut-off criterion. The life cycle data reported for seedlings included the production and transportation of 20 g of peat [60]. The distribution distance was assumed as regional (50 km) and the seedling were obtained at the local market (5 km).
- Water: Water consumption depended on the crop period length and the season. As mentioned in Section 2.1, a homogeneous irrigation rate between $5 \text{ L}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ and $7 \text{ L}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ of tap water was provided to the crops depending on the season. Irrigation rate was lower for cold days (01/10 to 30/04) than for warm days (01/05 to 30/09), in order to adapt to plant evapotranspiration. Irrigation was performed manually, implying that the gardener opened and closed the tap to provide the required amount of water without the need for auxiliary equipment to time and regulate the same.
- Organic fertilization: Industrial compost was used for organic mineralization. LCI for the manufacturing of industrial compost was obtained from the literature [61].
- Mineral fertilization: NPK 6-12-24 and ammonium nitrate were employed as mineral fertilizers (dosages indicated above).
- N air emissions from fertilization: Air emissions of different nitrogen components occurred due to the application of fertilizers, depending on the content of nitrogen and its form. According to Audsley [62] and Brentrup et al. [63], the NH_3 volatilization from simple fertilizers was considered as 2% of the total nitrogen content (Equation (1)), and 4% for complex fertilizers

(i.e., NPK) (Equation (2)). The N₂O emissions represented 1.25% of the total nitrogen content (Equation (3)) and NO_x emissions were 10% of the N₂O emissions (Equation (4)). The total amount in the three fertilizers depended on the nitrogen content and humidity. Data from producers were obtained for this calculation: 2.15% nitrogen content and 37% humidity for compost; 6% nitrogen content for NPK, and 34% nitrogen content for ammonium nitrate:

$$N - \text{NH}_3 \text{ emission (kg)} [N - \text{simple}] = 0.02 \times N_{\text{total}} \text{ (kg)} \quad (1)$$

$$N - \text{NH}_3 \text{ emission (kg)} [N - \text{NPK}] = 0.04 \times N_{\text{total}} \text{ (kg)} \quad (2)$$

$$N - \text{N}_2\text{O emission (kg)} = 0.0125 \times N_{\text{total}} \text{ (kg)} \quad (3)$$

$$N - \text{NO}_x \text{ emission (kg)} = 0.1 \times N - \text{N}_2\text{O emission (kg)} \quad (4)$$

- N lixiviates were excluded from the system boundaries as no measured data were available.
- Pest management: Pest control treatments were performed only once on crops, a few days after transplanting using 25 L of copper oxychloride (Cu₂(OH)₃Cl) at a concentration of 3.5 g·L⁻¹ (in well water).

(c) Waste Management

Waste management depended on the type of produced waste. A waste scenario was defined as follows for elements of auxiliary equipment: 50% recycled, including the transportation to the local recycling plant (10 km), and 50% final disposal in an incinerator, according to waste management facilities available in the area [64].

(d) Costs

Cost data for each element was collected to account for the total cost of the life cycle. Data for the purchased elements (e.g., nonwoven fabric, seeds) were obtained from specialized sellers in the study area. Due to the variability of seedlings' price in the market, an average from three different suppliers was used in this assessment. Tap water cost was obtained from the local water provider (Gruppo Hera). Distribution costs were considered as included in the product price when obtained by the gardener. The gardener's transport costs were estimated according to the vehicle model, the fuel consumption rate and the fuel price. Appendix A (Table A1, Table A2 and Table A3) shows the unitary cost data of different elements employed in this LCC.

2.2.3. Life Cycle Impact Assessment

Once the LCI was completed for each crop, the impact assessment phase of the LCA was performed by employing the software, Simapro 8.3.0 [65]. To classify and characterize each flow, as mandatory steps of the ISO 14040-44 [57,66], the ReCiPe method [67] was chosen. Midpoint characterization factors and a hierarchical perspective were used as recommended by global guidelines [59]. The indicators included in this assessment were: climate change (CC, kg CO₂ eq.), ozone depletion (OD, kg CFC-11 eq.), terrestrial acidification (TA, kg SO₂ eq.), freshwater eutrophication (FEU, kg P eq.), marine eutrophication (MEU, kg N eq.), human toxicity (HT, kg 1.4-DB eq.), photochemical oxidant formation (POF, kg NMVOC), particulate matter formation (PMF, kg PM₁₀ eq.), terrestrial ecotoxicity (TET, kg 1.4-DB eq.), freshwater ecotoxicity (FET, kg 1.4-DB eq.), marine ecotoxicity (MET, kg 1.4-DB eq.), ionising radiation (IR, kBq U₂₃₅ eq.), agricultural land occupation (ALO, m²a), urban land occupation (ULO, m²a), natural land transformation (NLT, m²), water depletion (WD, m³), metal depletion (MD, kg Fe eq.), and fossil depletion (FD, kg oil eq.).

2.2.4. Life Cycle Costing

For life cycle costing, the costs of different elements were aggregated by life cycle stages. The total cost was compared to the price in the market of each product. Three market prices were considered

for the assessment: Italian market (data from national statistics [68]), bio market (data from a farmers' association [69]), and the local market (data from a local farmer).

2.2.5. Data Quality and Geographical Adaptation

LCI data of the home-garden products were collected from the cultivation system of the case study (primary data). LCI data regarding material extraction, processing, transportation and electricity generation were obtained from the ecoinvent database 3.0 [70], while literature data were used for compost production [61] (background data). When background data was employed, the datasets were adapted to the geographical context of the case study of Padua (Italy), thereby indicating the consumption of Italian resources (e.g., natural gas, electricity, water) and of materials produced in their origin markets. Background data was adapted to the geographical context of the study area. In this sense, the consumption of local resources was allocated to Italian resources and the consumption of energy adapted to the Italian market.

2.3. Food Security Potential

The food security potential was evaluated as the capacity of the garden to satisfy the vegetables requirements of the gardener, according to consumption and health recommendations. As multiple statistics with a different level of detail can be employed as reference, food security was evaluated for three baseline scenarios:

- **HEALTH:** The World Health Organization (WHO) indicates that a healthy diet contains, "At least 400g (five portions) of fruits and vegetables a day", excluding potatoes, sweet potatoes, cassava and other starchy roots [71].
- **SUPPLY:** The Food Balance Sheets of the Food and Agriculture Organization of the United Nations (FAO/UN) indicated that food supply in 2013 in Italy for vegetables was of 123.13 kg·year⁻¹·p⁻¹ [72].
- **CONSUMPTION:** The average Italian consumption, according to data from the Italian National Food Consumption Survey (INRAN-SCAI 205-06) [73], accounted for the daily average consumption of vegetables as 211.2 g·day⁻¹ (including 43.1 g of leafy vegetables, 41.9 g of tomatoes and 30.9 of other fruiting vegetables).

3. Results

This section displays the results of assessment of urban food production in the home garden.

3.1. Environmental Impact of a Home Garden

The environmental impact for different indicators of the home garden is shown in Table 3; they include impact per product (i.e., home-grown food), impact per area, and the total impact of garden activity. The impact and causes of each indicator is described below.

Climate change: The average climate change impact of home-grown products was 0.268 kg CO₂ eq·kg⁻¹. The contribution to climate change was associated with the emissions of carbon dioxide (CO₂), dinitrogen monoxide (N₂O), and methane (CH₄). Carbon dioxide originated as direct emission during the municipal solid waste (MSW) collection service (organic fertilization) and as indirect emission in the consumption of tap water and the production process of ammonium nitrate, which required electricity; non-renewable energy sources were also employed in the Italian electricity mix (i.e., hard coal, natural gas and oil). Dinitrogen monoxide was mainly emitted in the production process of ammonium nitrate and during the MSW collection service. Methane emission occurred mainly as indirect emission during the landfill process of the MSW that was discarded during industrial compost production.

Table 3. Environmental impact results per home-grown food [kg], per area [m²], and for the entire garden.

Indicator	Unit	Home-Grown Food	Area	Garden
Climate change (CC)	kg CO ₂ eq	2.68×10^{-1}	1.32	4.34×10^1
Ozone depletion (OD)	kg CFC-11 eq	1.38×10^{-8}	6.80×10^{-8}	2.24×10^{-6}
Terrestrial acidification (TA)	kg SO ₂ eq	1.43×10^{-3}	7.03×10^{-3}	2.32×10^{-1}
Freshwater eutrophication (FEU)	kg P eq	8.68×10^{-5}	4.27×10^{-4}	1.40×10^{-2}
Marine eutrophication (MEU)	kg N eq	3.66×10^{-4}	1.80×10^{-3}	5.92×10^{-2}
Human toxicity (HT)	kg 1.4-DB eq	2.25×10^{-1}	1.10	3.64×10^1
Photochemical oxidant formation (POF)	kg NMVOC	8.72×10^{-4}	4.29×10^{-3}	1.41×10^{-1}
Particulate matter formation (PMF)	kg PM ₁₀ eq	4.30×10^{-4}	2.11×10^{-3}	6.96×10^{-2}
Terrestrial ecotoxicity (TET)	kg 1.4-DB eq	3.52×10^{-5}	1.73×10^{-4}	5.69×10^{-3}
Freshwater ecotoxicity (FET)	kg 1.4-DB eq	2.17×10^{-2}	1.07×10^{-1}	3.51
Marine ecotoxicity (MET)	kg 1.4-DB eq	1.91×10^{-2}	9.40×10^{-2}	3.09
Ionizing radiation (IR)	kBq U ₂₃₅ eq	1.77×10^{-2}	8.70×10^{-2}	2.86
Agricultural land occupation (ALO)	m ² a	5.66×10^{-3}	2.78×10^{-2}	9.16×10^{-1}
Urban land occupation (ULO)	m ² a	7.41×10^{-2}	3.64×10^{-1}	1.20×10^1
Natural land transformation (NLT)	m ²	3.84×10^{-5}	1.88×10^{-4}	6.21×10^{-3}
Water depletion (WD)	m ³	5.94×10^{-1}	2.92	9.62×10^1
Metal depletion (MD)	kg Fe eq	4.08×10^{-2}	2.01×10^{-1}	6.61
Fossil depletion (FD)	kg oil eq	5.09×10^{-2}	2.50×10^{-1}	8.23

Ozone depletion: Ozone depletion impact was of 1.38×10^{-8} kg CFC-11 eq·kg⁻¹ home-grown food, on an average. Ozone depletion was caused by methane emissions in the form of bromotrifluoromethane (Halon 1301) and bromochlorodifluoromethane (Halon 1211) from tap water consumption, ammonium nitrate production, and industrial compost use.

Terrestrial acidification: The contribution to terrestrial acidification was, on an average, 1.43×10^{-3} kg SO₂ eq·kg⁻¹ home-grown food. Sulfur oxide (SO₂), ammonia (NH₃) and nitrogen oxides (NO_x) emissions were the main contributors to terrestrial acidification. These emissions were produced during tap water supply (sulfur dioxide, nitrogen oxides), ammonium nitrate production (ammonia), compost production (ammonia, nitrogen oxides), N-fertilizers application (ammonia), and pesticide production (sulfur oxide).

Freshwater eutrophication: The impact on freshwater eutrophication was 8.68×10^{-5} kg P eq·kg⁻¹, on an average. Sulfate emissions to water were produced in the pest management stage, due to lixivates in mining operations to obtain copper.

Marine eutrophication: The contribution to terrestrial acidification was, on an average, 3.66×10^{-4} kg N eq·kg⁻¹ home-grown food. Emissions of ammonium (NH₄⁺), nitrogen (N, organic) and nitrate (NO₃) to water were mainly produced as lixivates in the landfilling of discarded MSW from industrial compost production. Nitrogen oxides and ammonia emissions to air resulted from electricity consumption in the tap water system, from the production of ammonium nitrate (nitric acid production) and industrial compost (MSW collection, electricity consumption), and direct emissions of applying N-fertilizers.

Human toxicity: The ozone depletion impact was of 2.25×10^{-1} kg 1.4-DB eq·kg⁻¹ home-grown food, on an average. Manganese emissions to water were produced as lixivates during mining operations to obtain copper (pest management) and the landfilling of discarded MSW in the industrial compost process (organic fertilization).

Photochemical oxidant formation: The average photochemical oxidant formation of home-grown products was of 8.72×10^{-4} kg NMVOC·kg⁻¹. NO_x, NMVOC, SO₂ and CH₄ emissions to air were the main contributors, mainly due to the electricity consumed along the life cycle, the emissions of transport use (particularly during MSW collection) and the landfilling of MSW (compost production).

Particulate matter formation: The contribution to particulate matter formation was, on an average, 8.72×10^{-4} kg PM₁₀ eq·kg⁻¹ home-grown food. The impact was mainly caused by NO_x, SO₂, PM_{2.5}, NH₃ and particulates emissions to air. A large share of these emissions occurred during the production

stage of the electricity consumed in the tap water service, direct emissions from the MSW collection service in compost production, pesticides production, and direct emissions when applying N-fertilizers.

Terrestrial ecotoxicity: The terrestrial ecotoxicity impact was of 3.52×10^{-5} kg 1.4-DB eq. \cdot kg⁻¹ home-grown food, on average. The emissions contributing to this impact were copper, zinc and vanadium emissions to air, cypermethrin and aldicarb emissions to soil, and bromine emissions to water during the stages of tap water consumption, organic fertilizers, and mineral fertilizers. Beyond these, chlorine emissions to water during the treatment of tap water were the second-most impacting ones.

Freshwater ecotoxicity (FET): The average freshwater ecotoxicity of home-grown products was of 2.17×10^{-2} kg 1.4-DB eq. \cdot kg⁻¹. The largest contributors to this impact were emissions to water of copper (compost production), nickel (compost production and tap water consumption), zinc (compost production and pesticides production), and manganese (pesticides production).

Marine ecotoxicity (MET): The contribution to marine ecotoxicity was, on an average, 1.91×10^{-2} kg 1.4-DB eq. \cdot kg⁻¹ home-grown food. The same emissions to water as of FET were the major contributors.

Ionizing radiation (IR): The impact of ionizing radiation was 1.77×10^{-2} kg U₂₃₅ eq. \cdot kg⁻¹, on average. Emissions of Carbon-14 and Radon-222 to air were produced in nuclear plants feeding the electricity market in Italy.

Agricultural land occupation (ALO): The agricultural land occupation was 5.66×10^{-3} m² \cdot a \cdot kg⁻¹ home-grown food, on average. The occupation of forest land occurred in the electricity production in Italy, mainly in two processes: wood employed in biomass co-generation plants and wood used in mine infrastructure for hard coal extraction for electricity production.

Urban land occupation (ULO): The average urban land occupation of home-grown products was of 7.41×10^{-2} m² \cdot a \cdot kg⁻¹. The direct occupation of the garden itself was the main contributor to this impact category.

Natural land transformation (NLT): The contribution to natural land transformations was, on average, 3.84×10^{-5} m² \cdot kg⁻¹ home-grown food. Transformation of sea and ocean, forest and extensive forest land uses were caused by electricity production, according to the Italian mix, particularly during natural gas and heavy fuel oil extraction procedures.

Water depletion (WD): The average depletion of water resources for home-grown products was of 5.95×10^{-1} m³ \cdot kg⁻¹. Water was mainly directly consumed for crop irrigation. However, indirect consumption of water occurred in the processing of different fertilizers, particularly industrial compost, due to the use of electricity and water employed for turbine use.

Metal depletion (MD): Metal depletion was 4.08×10^{-2} kg Fe eq. \cdot kg⁻¹, on average. Most of the metal depletion was associated with the copper consumed for producing the pesticide (copper sulfate). Copper employed in the water supply network was also a relevant contribution.

Fossil depletion (FD): Fossil depletion impact was 5.09×10^{-2} kg oil eq. \cdot kg⁻¹ home-grown food, on average. Depletion of oil, natural gas and hard coal occurred in energy-consuming activities of the life cycle—electricity and fuels.

Normalized Values for the European Region

When the midpoint indicators were normalized for the European region, the most relevant indicator categories rose. Marine ecotoxicity (40.9%) and freshwater ecotoxicity (36.7%) had the largest contributions. In the second tier, human toxicity (6.6%), nature land transformation (4.3%), freshwater eutrophication (3.9%) and urban land occupation (3.2%) had relevant contribution. The indicators that showed a lower relevance were ozone depletion, terrestrial ecotoxicity, ionizing radiation, agricultural land occupation and water depletion, with contributions lower than 0.1%. The average contribution of the 18 indicators to the normalized value is shown in Appendix B (Figure A1).

3.2. Contribution of Life Cycle Stages

Figure 3 shows the contribution of the different life cycle stages to each environmental indicator. The highest contributing stages were fertilization (both organic and mineral), tap water consumption, and pesticides.

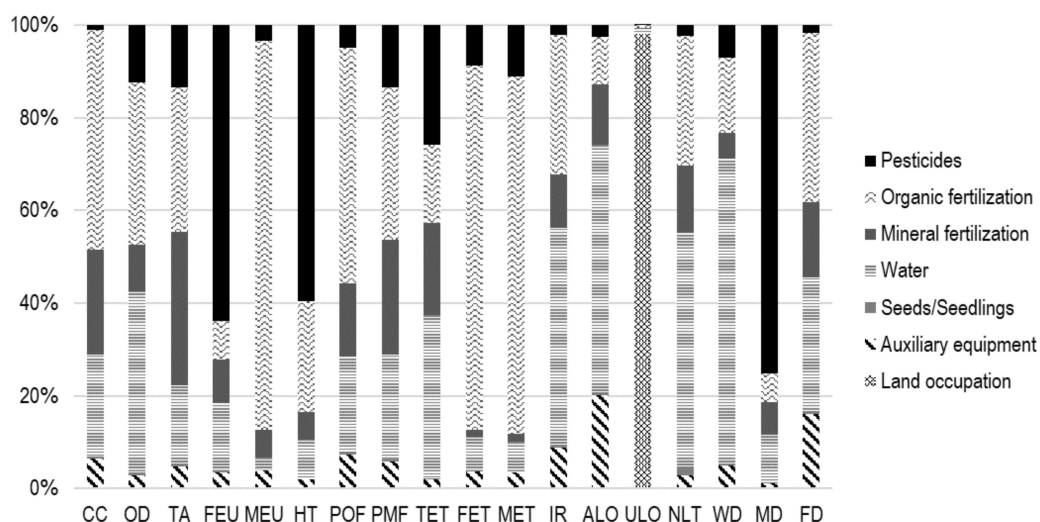


Figure 3. Contribution of the different life cycle stages to environmental impact indicators. The included indicators are climate change (CC, kg CO₂ eq.), ozone depletion (OD, kg CFC-11 eq.), terrestrial acidification (TA, kg SO₂ eq.), freshwater eutrophication (FEU, kg P eq.), marine eutrophication (MEU, kg N eq.), human toxicity (HT, kg 1.4-DB eq.), photochemical oxidant formation (POF, kg NMVOC), particulate matter formation (PMF, kg PM₁₀ eq.), terrestrial ecotoxicity (TET, kg 1.4-DB eq.), freshwater ecotoxicity (FET, kg 1.4-DB eq.), marine ecotoxicity (MET, kg 1.4-DB eq.), ionising radiation (IR, kBq U₂₃₅ eq.), agricultural land occupation (ALO, m²a), urban land occupation (ULO, m²a), natural land transformation (NLT, m²), water depletion (WD, m³), metal depletion (MD, kg Fe eq.), and fossil depletion (FD, kg oil eq.).

Organic fertilization: Compost production, transportation and application contributed to between 0.5% to 83.9% of the environmental impact, 34% on average. This was the largest contributing stage for MEU (83.9%), FET (78.6%), MET (77.0%), POF (50.9%), CC (47%), PMF (32.9%) and FD (36.5%).

Water: The consumption of tap water was the second most contributing element of the life cycle (25.2%, on average), with contributions to the indicators ranging from 1.1 to 66.0%. Water had the largest impact in WD (66.0%), ALO (53.6%), NLT (51.0%), IR (46.7%), OD (39.1), TET (35.2%) and MD (10.4%).

Mineral fertilization: The mineral fertilizers life cycle stage contributed to the impact categories between 0.22% to 33.0% (12.1%, on average). Mineral fertilizers had the largest contribution to TA (33.0%) and was the second-most relevant stage in the indicators of CC (22.7%) and PMF (24.9%).

Pesticides: The contribution of pesticides to the life cycle impact varied from 0.1 to 75.2%, depending on the indicator (average contribution of 17.2%). Being the major contributor to MD (75.2%), FEU (63.8%) and HT (59.6%), this stage also had a relevant impact on TET (25.9%).

Other life cycle stages: Auxiliary equipment had a relevant contribution to the ALO (20.2%) and FD (16.1%) indicators, although the average contribution was 5.6%. Land occupation by the home garden contributed to the ULO (98%) and FD (5.5%) categories, with no attributed impact to the rest of the indicators. The production of seeds, production of substrate for seedlings, and their transportation had the lowest contribution to the overall impact (<1.6% for all the categories—0.4% on average).

3.3. Home Garden Design: Crop Impacts

When evaluating each crop individually, the environmental impact assessment showed a common pattern for different indicators, as crop management practices were mostly homogeneous (apart from some protected crops and some crops without mineral fertilization, e.g., crop rotations). For all the indicators, the lowest impact was shown for spring-summer crops of chicory, tomato (both bunch and table) and eggplant, as well as a winter crop of chard. The most impacting ones were a summer-autumn crop of chicory, a winter crop of peas and the two spring-summer crops of string beans. Figure 4a shows the environmental impact of the 21 crops under assessment for climate change, as an example of this trend.

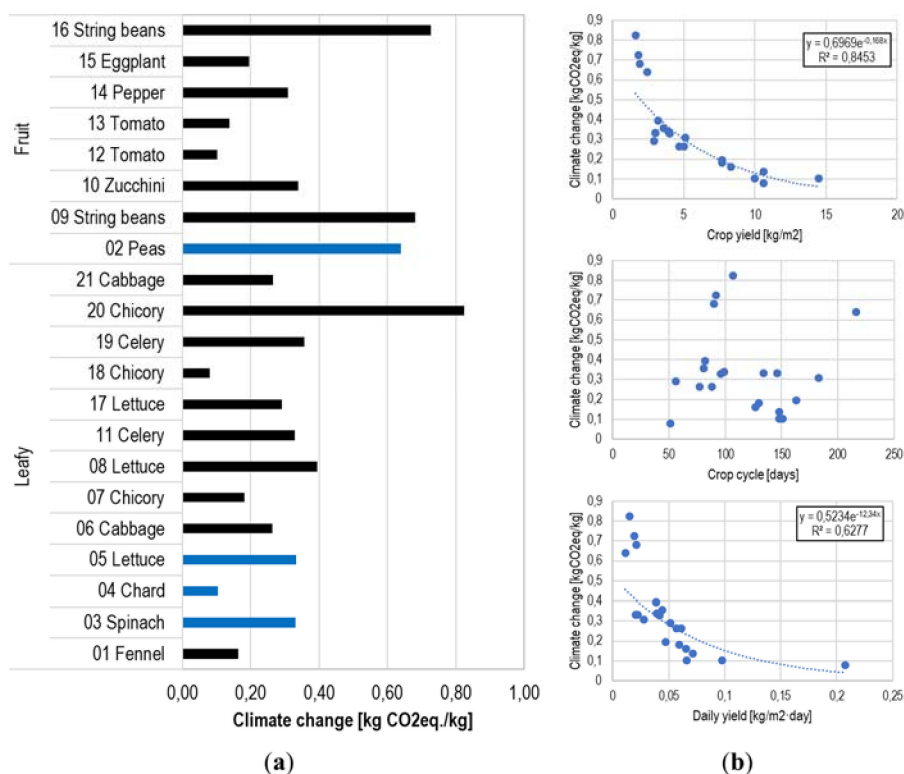


Figure 4. Climate change impact of home garden crops: (a) Results for the 21 crops under assessment, including unprotected crops (black) and protected crops (blue); and (b) Correlation between climate change impact and crop yield, crop cycle, and daily yield. Crops can be identified according to the values of crop yield and crop cycle from Table 1.

The correlation between the environmental impact and the agronomical characteristics of each crop was evaluated to identify the main factors determining environmental impact. Crop yield and crop cycle were tested for all the indicators. While crop yield resulted in a determining factor for all the indicators with a high correlation ($R^2 = 0.77$ – 0.91), crop cycle showed no correlation nor pattern. When crop yield and crop cycle were combined in a daily crop yield parameter, environmental impacts showed moderate correlation for all the indicators ($R^2 = 0.52$ – 0.72). Figure 4b displays the correlation assessment for climate change.

Table 4 includes the environmental impact results (average, minimum and maximum) for the different indicators by type of vegetable: leafy (fennel, spinach, chard, lettuce cabbage, chicory, celery) and fruit (peas, string beans, zucchini, tomato, pepper, eggplant). On average, leafy vegetables had a 30% lower environmental impact than fruit vegetables.

Table 4. Average, minimum, and maximum environmental impact value for each LCIA indicator, by type of vegetable (leafy, fruit).

LCIA	Unit	Leafy			Fruit		
		AVG	MIN	MAX	AVG	MIN	MAX
CC	kg CO ₂ eq	3.01×10^{-1}	7.92×10^{-2}	8.24×10^{-1}	4.43×10^{-1}	7.92×10^{-2}	7.26×10^{-1}
OD	kg CFC-11 eq	1.55×10^{-8}	4.41×10^{-9}	4.05×10^{-8}	2.27×10^{-8}	4.41×10^{-9}	3.57×10^{-8}
TA	kg SO ₂ eq	1.58×10^{-3}	3.73×10^{-4}	4.51×10^{-3}	2.38×10^{-3}	3.73×10^{-4}	3.98×10^{-3}
FEU	kg P eq	1.03×10^{-4}	3.31×10^{-5}	2.64×10^{-4}	1.40×10^{-4}	3.13×10^{-5}	2.33×10^{-4}
MEU	kg N eq	4.51×10^{-4}	1.55×10^{-4}	1.13×10^{-3}	5.85×10^{-4}	1.27×10^{-4}	9.99×10^{-4}
HT	kg 1.4-DB eq	2.74×10^{-1}	9.30×10^{-2}	6.87×10^{-1}	3.60×10^{-1}	7.90×10^{-2}	6.09×10^{-1}
POF	kg NMVOC	1.00×10^{-3}	2.90×10^{-4}	2.65×10^{-3}	1.43×10^{-3}	2.90×10^{-4}	2.33×10^{-3}
PMF	kg PM ₁₀ eq	4.79×10^{-4}	1.23×10^{-4}	1.32×10^{-3}	7.10×10^{-4}	1.23×10^{-4}	1.17×10^{-3}
TET	kg 1.4-DB eq	3.88×10^{-5}	9.95×10^{-6}	1.06×10^{-4}	5.82×10^{-5}	9.95×10^{-6}	9.33×10^{-5}
FET	kg 1.4-DB eq	2.67×10^{-2}	9.40×10^{-3}	6.57×10^{-2}	3.46×10^{-2}	7.55×10^{-3}	5.83×10^{-2}
MET	kg 1.4-DB eq	2.36×10^{-2}	8.31×10^{-3}	5.81×10^{-2}	3.05×10^{-2}	6.64×10^{-3}	5.15×10^{-2}
IR	kBq U ₂₃₅ eq	1.93×10^{-2}	5.04×10^{-3}	5.10×10^{-2}	2.92×10^{-2}	5.04×10^{-3}	4.62×10^{-2}
ALO	m ² a	5.84×10^{-3}	1.24×10^{-3}	1.57×10^{-2}	9.44×10^{-3}	1.24×10^{-3}	1.66×10^{-2}
ULO	m ² a	7.60×10^{-2}	1.44×10^{-2}	1.96×10^{-1}	1.20×10^{-1}	1.44×10^{-2}	2.56×10^{-1}
NLT	m ²	4.16×10^{-5}	1.09×10^{-5}	1.12×10^{-4}	6.33×10^{-5}	1.09×10^{-5}	9.95×10^{-5}
WD	m ³	6.33×10^{-1}	1.59×10^{-1}	1.64	9.82×10^{-1}	1.59×10^{-1}	1.63
MD	kg Fe eq	4.96×10^{-2}	1.65×10^{-2}	1.24×10^{-1}	6.55×10^{-2}	1.44×10^{-2}	1.10×10^{-1}
FD	kg oil eq	5.62×10^{-2}	1.47×10^{-2}	1.51×10^{-1}	8.39×10^{-2}	1.47×10^{-2}	1.32×10^{-1}

3.4. Economic Cost and Eco-Efficiency Analysis

Life cycle costing (LCC) accounted for the overall costs of the home garden vegetables. The average cost of the home-grown vegetables was of 1.57 €·kg⁻¹, ranging from 0.46 € to 3.56 €. The different life cycle stages contributed in a different manner. On average, seedlings were the most-expensive element of the life cycle (45%), followed by the compost employed as organic fertilizer (27%) and tap water for irrigation (17%). Mineral fertilizers (6%), pesticides (3%) and elements of the auxiliary equipment (2%) were the cheapest elements. When comparing the total cost with the market prices (Italian market, bio market and local market), home-grown vegetables were cheaper than market vegetables, apart from three crops—the two cycles of celery and the chicory variety ‘Treviso’ (Appendix C, Figure A2). Therefore, the home garden offered economic savings due to food self-production to the gardener.

The relationship between the environmental impact and the economic cost was analyzed through eco-efficiency charts, to identify best crops and desired trends. The analysis unveiled three areas of the chart: eco-efficient crops (A), high-impact low-cost crops (B) and low-impact high-cost crops (C). The same pattern was found for the different indicators under assessment. Figure 5 illustrates this pattern for CC, WD, HT and FET.

Eco-efficiency crops (A) included a variety of leafy vegetables and tomatoes, which were the crops performing best as fruit vegetables. In area B, there were crops with a low-crop yield: chicory, string beans and peas. The area C included some fruit vegetables (pepper, zucchini, eggplant) and leafy vegetables (celery, lettuce) mainly due to the high cost of seedlings. The desirable trend (indicated with grey arrows in Figure 5) would be to decrease the impact of B-area crops as well as the price of C-area crops, while improving crop performance of certain vegetables and finding alternatives to expensive seedlings.

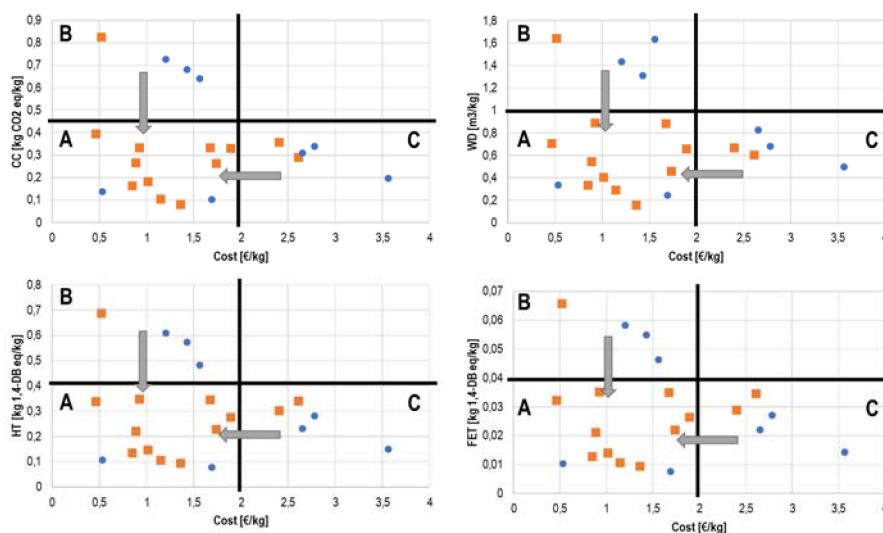


Figure 5. Eco-efficiency of home gardening for climate change (CC), water depletion (WD), human toxicity (HT) and freshwater ecotoxicity (FET). The chart includes leafy vegetables (orange squares) and fruit vegetables (blue dots). Grey arrows indicate desired trend.

3.5. Food Security Potential

According to production values, the total harvest of 161.8 kg of vegetables could represent supply for between 1.11 and 2.10 people in the gardener’s household (Figure 6). Such figures represent that, with the evaluated crop design and outputs, a person could satisfy their vegetable requirements with a garden size of between 11.9 m² and 22.6 m² (Figure 6). However, one may notice that the most restricting food security perspective—the health perspective of 400g of fruit and vegetables a day—considers full accomplishment only with vegetables. From a consumption perspective, the production of the home garden can fulfill the annual requirements of 5.6 persons for leafy vegetables, 1.6 persons for tomatoes and 4.3 persons for other fruit vegetables.

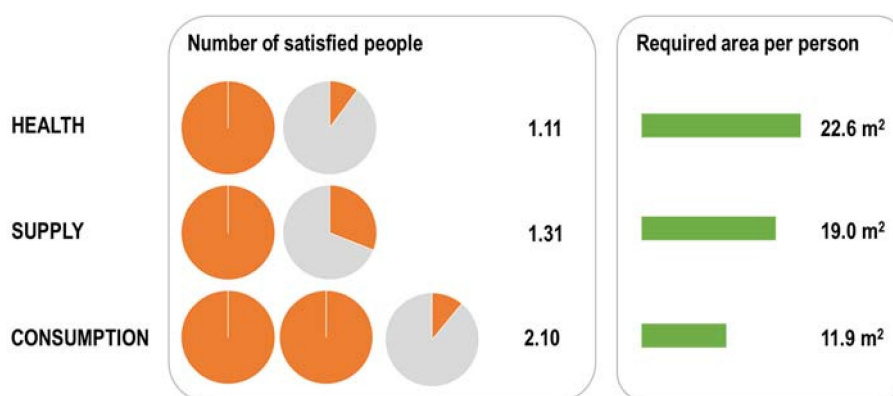


Figure 6. Food self-sufficiency potential of the home garden in terms of number of satisfied people and the corresponding required area per person, from a health, supply and consumption perspective.

4. Discussion

This study evaluated the environmental, economic and food security impact of home gardens as a traditional form of UA. In the context of available literature, the environmental impact of this home garden was within the range of open-air UA production. For climate change (Figure 7), tomato and lettuce environmental data were available for different UA forms and case studies. Home-grown tomatoes had a slightly higher environmental impact than soil-based urban farms in the United

States [47] and a rooftop garden in Italy [48]. The impact was significantly lower when compared to an open-air rooftop farm in the USA [47] and community farming with organic practices in the United Kingdom [50]. In the case of lettuce, differences with other case studies were less significant, apart from a urban farm case in the USA with a high crop yield performance [47].

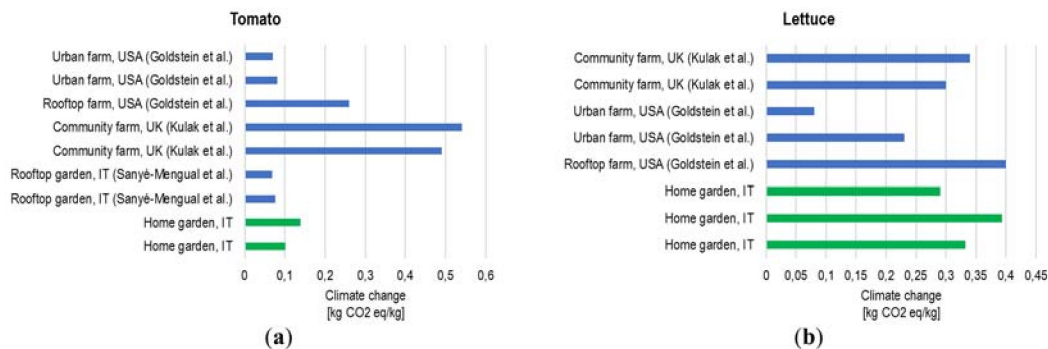


Figure 7. Comparison of the climate change impact of tomato (a) and lettuce (b) production in the home garden under assessment with open-air UA production literature data.

While for home gardens, tap water, fertilization and pest management were the most relevant life cycle stages in the different environmental impact categories, differences were found with other case studies in the literature. The community rooftop garden in Bologna (Italy) employed electrical devices for automatic fertigation of the garden leading to a large consumption of electricity. Due to the current electricity mix in Italy, this resource consumption had a relevant impact on the environmental indicators [48]. Furthermore, the cost of the auxiliary equipment required for this automatization was also the main contributor to the life cycle costing [48]. In this home garden, the employment of manual techniques was enhanced, and thus offered a higher eco-efficiency. Both, Goldstein et al. [47] and Kulak et al. [50] identified the embodied greenhouse gas emissions (GHG) of the capital resources (i.e., materials of the structure and the auxiliary equipment) as the largest contribution to global warming. However, our study did not find differences between the same product when employing auxiliary equipment (e.g., tunnel), as the specific variety and the crop yield were more determinant in the environmental impact value.

4.1. Eco-Efficiency and Crop Management

The environmental assessment indicated that organic fertilization, use of tap water, mineral fertilization and pesticides were the most contributing elements of the life cycle. The case study under assessment followed low-input agronomic practices, minimizing the consumption of certain resources. In particular, this home garden showed a great advantage of employing a manual management, while avoiding the use of electronic devices to automatize irrigation, which was a relevant element of the environmental burdens of community gardening in a case study in Bologna (Italy) [48]. Along the same lines, these manual practices also benefited the economic cost of the home-grown products, which resulted in economic savings for the gardener.

According to the results of this study, crop management could be improved to minimize environmental burdens and economic costs. First, the dosages of fertilizers, water and pesticides could be adapted to crop requirements, avoiding the current homogeneous application. The need of differentiating dosages according to diverse crops was already highlighted in the literature of urban agriculture [36,48]. For this case study, the applied rates of nitrogen fertilization were around $220 \text{ kg N}\cdot\text{ha}^{-1}$ in most of the crop cycles. Although this rate remained within the range of previous indications for vegetable crops (e.g., 89 to $190 \text{ kg N}\cdot\text{ha}^{-1}$ for tomatoes [74], 145 to $344 \text{ kg N}\cdot\text{ha}^{-1}$ for lettuces [75,76], 180 to $600 \text{ kg N}\cdot\text{ha}^{-1}$ for cabbage [77]), the amount could result in significant leaching losses. Furthermore, the winter irrigation rate was larger than the expected rate in professional

agriculture. These aspects highlighted the relevance of agricultural knowledge in crop management, the resulting resources consumption and the consequent environmental impacts and economic costs.

Second, the use of organic compost was linked to large contributions to environmental impacts due to the origin of organic waste, i.e., municipal solid waste. The employment of specific typologies of compost with green waste could reduce such impacts. Furthermore, self-composting could be performed in the garden by employing household and garden bio-waste, promoting a closed system that would provide these urban wastes with a second life, as usually enhanced in UA practices [78]. Third, tap water could be substituted by alternative water sources that are not linked to the water provision system, such as rainwater harvesting. Finally, the use of pesticides showed large burdens in eco-toxicity categories and, thus, a reduced use of these chemicals by employing integrated pest management would positively affect these impact categories, as promoted by the Directive of Sustainable use of pesticides [79]. Furthermore, such an approach would indirectly benefit the biodiversity of the garden and the ecosystem services related to habitat provision and pollination.

4.2. Implications of Crop Design

The evaluation of multiple vegetable crops unveiled the relevance of garden design and crop selection in the eco-efficiency of home gardens. The varieties of certain species can largely affect the environmental and economic outputs as the performance, i.e., crop yield, can vary. In this case study, different varieties of chicory, lettuces and tomato were cultivated. In the case of chicory, the “Catalogna” variety yielded almost 10 times more than “Treviso”. This fact resulted in “Catalogna” being the least impacting crop in environmental terms and “Treviso” the most impacting one. On the contrary, the two varieties of lettuce—“Gentile” and “Cappuccia”—showed no significant difference in terms of crop yield or environmental impact. Finally, tomato varieties (bunch and table) showed crop yield and environmental impact differences but were still the least-impacting fruit vegetable crops.

Less eco-efficient varieties may be substituted by new crops in the garden to diversify the harvest, as polyculture home gardens are beneficial towards ensuring food security and improving healthy diet habits [80]. On the other hand, leguminous crops were the most impacting ones in environmental terms among the fruit crops. However, such crops provide a source of vegetable protein to the gardener and more environmentally-friendly practices may be applied instead of substituting such species from the garden design.

According to the food security analysis, the assessed home garden could satisfy the food requirements of between 1 and 2 members of the household, depending on the considered perspective. Considering the most restricting perspective (health perspective: 400g of fruit and vegetables a day), food security could be improved through crop design by including fruit crops (e.g., melon, watermelon, strawberries) as new crops, which could substitute the least eco-efficient varieties identified in this study. Such changes will increase not only eco-efficiency but also food security. Fruit crops were included in the design of the community rooftop garden in Bologna, Italy, satisfying the vegetables and fruit requirements of some social housing inhabitants who participated in garden management [81].

5. Conclusions

This paper contributed to literature with the first comprehensive evaluation of the economic and environmental burdens of home gardens as a form of UA. Furthermore, the food security potential of the garden was evaluated to deepen the role of home gardens in urban food systems. The environmental burdens of a home garden were mostly related to crop practices, as a low-input type of UA characterized by low automatization and manual labor. Furthermore, economic costs can be affected by the niche market of urban gardening, such as the high costs of seedlings.

The practices recommended to improve the eco-efficiency of home gardens should focus on minimization of the use of chemicals, promotion of renewable and endogenous resources (e.g., rainwater, home-made compost), diffusion of nursing, and integrated pest management. The design of the garden and the crop selection can determine the overall impact of the garden,

as certain varieties yield better, and can make a more diversified contribution to household food security.

Further research may focus on the eco-efficiency assessment of best practices to minimize the environmental and economic burdens of home gardens. The quantification and inclusion of other social benefits of home gardening, beyond food security, may shed light on the comprehensive contribution to sustainability of home gardening. The analysis of other case studies in the same study area (Padua, Veneto) as well as in Italy could provide further evidence, beyond this case study, as a basis for cross-case learning, results generalization, and identification of best practices towards sustainable home gardens. To improve LCI coverage, direct measurements of lixiviates might be included in further assessments. Finally, as climatic conditions are determinants for agricultural production, the replication of this assessment in home gardens of different climatic areas may provide further knowledge on the geographic variability and effects on sustainability impacts of home gardening.

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Appendix A. Cost Data

Table A1 displays the unitary cost per element of the life cycle of home-grown food.

Table A1. Unitary cost and source, by element of the life cycle of home-grown food (* For seeds and seedlings, a range of the price is here provided, as it depends on the variety, see Tables A2 and A3).

Element	Cost	Unit	Source
Land occupation	-		
Nonwoven fabric	11.75	€/kg	Specialized seller
Tunnel rods	5.55	€/kg	Specialized seller
Plant net	12.55	€/kg	Specialized seller
Tubes	2.175	€/kg	Specialized seller
Tap water	0.00139	€/L	Local water provider
Seeds *	6.4–30	€/kg	Specialized seller
Seedlings *	0.14–3.53	€/p	Average of market prices
Industrial compost	1.6	€/kg	Specialized seller
NPK 6-12-24	5.50	€/kg	Specialized seller
Ammonium nitrate NH ₄ NO ₃	0.575	€/kg	Specialized seller
Copper sulfate	5.00	€/kg	Specialized seller
Distribution transport	0.206	€/kgkm	Estimation
Gardener transport	0.602	€/kgkm	Estimation

Table A2 displays the unitary cost per seedling, by crop. The values resulted from the average of the market price in three different nursery firms of the study area.

Table A2. Seedling cost, by crop.

Element	Cost	Unit
Fennel	0.31	€/seedling
Chard	0.36	€/seedling
Lett. Cappuccia	0.25	€/seedling
Cabbage cappuccio	0.30	€/seedling
Lett. Gentile	0.25	€/seedling
Zucchini	1.03	€/seedling
Celery	0.56	€/seedling
Tomato grappolo	0.94	€/seedling
Tomato tondo	0.94	€/seedling
Pepper	0.94	€/seedling
Eggplant	3.53	€/seedling
Chicory "Catalogna"	0.14	€/seedling
Chicory "Treviso"	0.26	€/seedling
Cabbage Verza	0.49	€/seedling

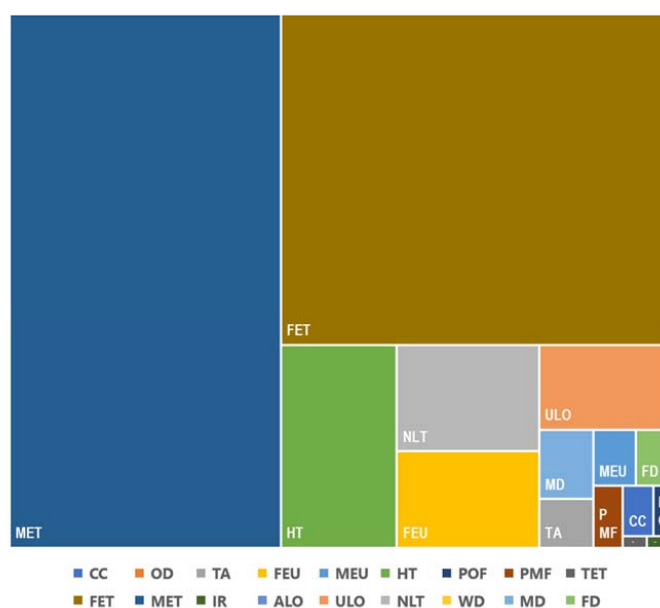
Table A3 shows the specific cost for seeds, by crop. Seeds' cost was obtained from the specialized seller that provided the seeds in this assessment.

Table A3. Seeds cost, by crop.

Element	Cost	Unit
Peas	6.8	€/kg
Spinach	24	€/kg
Chicory "grumolo"	22	€/kg
String beans	30	€/kg

Appendix B. Indicators' Contribution to the Normalized Impact

The following tree diagram displays the relevance of the different ReCiPe indicators in the normalized value:

**Figure A1.** Contribution of the individual ReCiPe midpoint indicators to the normalized value.

Appendix C. Cost Comparison with Market Prices

The total cost of home-grown products was compared with market prices, including the Italian market (national statistics), the bio market and the local market. The cost balance was calculated as:

$$\text{Cost balance} \left(\frac{\text{€}}{\text{kg}} \right) = \text{Market price} \left(\frac{\text{€}}{\text{kg}} \right) - \text{Total cost} \left(\frac{\text{€}}{\text{kg}} \right) \quad (\text{A1})$$

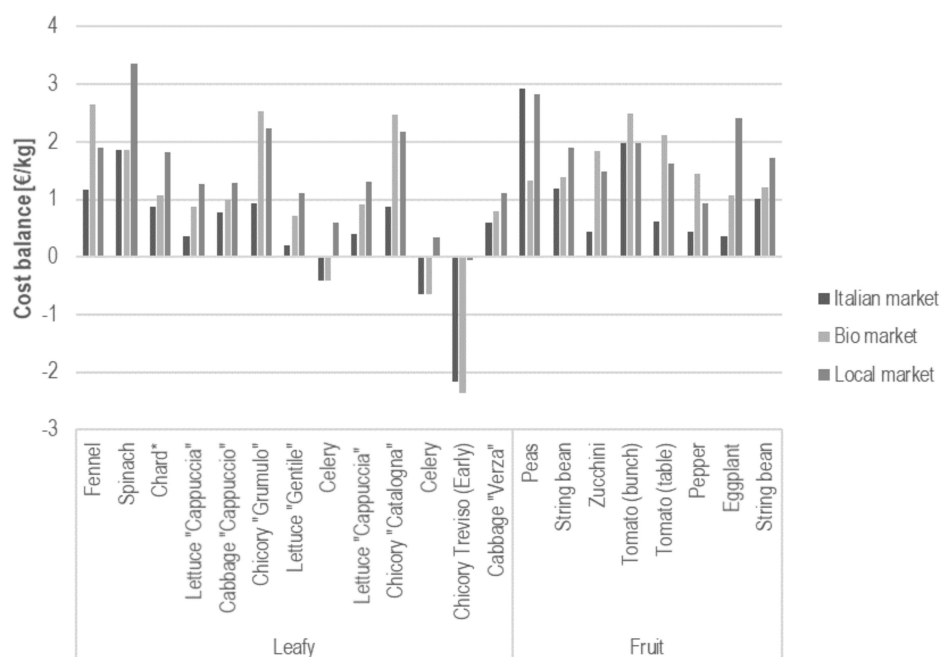


Figure A2. Cost balance comparing to the Italian market, bio market and local market, by crop and vegetable type.

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