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RESEARCH ARTICLE

A classification scheme for urban agriculture combining technical properties with characteristics related to the economic and social sustainability

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Abstract

Urban agriculture is often associated with sustainable agricultural practices. However, the variety of systems qualifying as urban agriculture and the limited information available about their sustainability question this direct relationship. To better understand differences in intra-urban agriculture systems and their sustainability, this paper proposed an holistic classification of urban agricultural systems and collected knowledge about the environmental, social, and economic sustainability of these systems. Such a classification is important to evaluate sustainability claims on urban agricultural systems, anticipate potential sustainability trade-offs between urban agricultural systems and propose preventive measures to address these, and ultimately guide the sustainable deployment of these systems. Compared with existing classifications, the novel classification scheme proposed here accounts for technological, social and economic characteristics of urban agriculture systems to better distinguish between all systems. It was built on 91 scientific papers. The economic intensity of production was, for example, an important characteristic to coherently group urban agriculture systems. The intensity of cooperation between all actors was another characteristic emphasized for certain urban agriculture systems. One end of the classification scheme describes ground-based open, socially motivated urban agriculture systems with high cooperation intensity and low production intensity. The other end of the classification scheme describes building-integrated quasi-closed systems with high production intensity. In between, we find: building-integrated conditioned systems, ground-based conditioned systems, and building-integrated open systems. Mapping sustainability claims from literature in the classification scheme supported its definition along the three characteristics. For example, urban farming was associated with job creation, food safety, water savings, and higher yields while urban gardening with educational potentials, biodiversity improvements, and lower yields. Their display in the classification scheme was therefore supported. To further support the use of the proposed scheme, additional quantitative research to better understand and quantify the sustainability of urban agriculture systems is required.

Keywords Environmental impact · Social impact · Economic impact · Life cycle assessment · Vertical farms · Urban farming · Urban gardening

1 Introduction

Urban agriculture (UA) is gaining interest as an alternative way of producing sustainable and healthy food. Several recent studies namely report social, economic, and environmental advantages of producing food in an urban setting (Specht et al. 2014; Kozai 2019). At the same time, a single definition of UA is not available. Mougeot's (2000) definition of urban agriculture was among the first ones and stated that "urban agriculture is an industry located within (intra-urban) or on the fringe (peri-urban) of a town, a city or a metropolis, which grows or raises, processes and distributes a diversity of food and non-food products, (re-)using largely human and material resources, products and services found in and around that urban area, and in turn supplying human and material resources, products and services largely to that urban area." More recently, Tornaghi (2014) also includes the edges of urban area in their definition of

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UA: "Urban agriculture is a broad term which describes food cultivation and animal husbandry on urban and peri-urban land." Similarly, the Food and Agriculture Organization of the United Nations defines UA as the "plant cultivation and animal rearing (including aquaculture) within cities and towns and in their immediate surroundings" (Orsini et al. 2020a). Lohrberg et al. (2015) focus more on the actors involved in UA and state that UA "spans all actors, communities, activities, places and economies that focus on biological production in a spatial context, which is categorized as urban." A more recent definition of Zhong et al. (2021) is similarly broad: "Urban agriculture is defined as production in the home or in plots within urban or periurban areas, which could increase urban residents' income and guarantee local food security and has the environmental advantages of reducing food transportation distances and thereby emissions." The broad definition of Zhong et al. (2021) allows to account for the fact that many systems described as "urban agriculture" can in reality be implemented in any "free space" available within or close to cities. Vegetables grown in an abandoned hallway of an industrial building or on the top of a high-rise building are both urban agriculture systems, despite the fact that the former may not necessarily be within a city. Another interesting aspect of the definition of Zhong et al. (2021) is the link made between urban agriculture and sustainability. This link between urban agriculture and sustainability is assumed valid in numerous publications (e.g., Specht et al. 2014; Kozai 2019), despite a significant lack of evidence. Only recently, Hawes et al. (2024) compared the carbon footprints of urban and conventional agriculture. Before, Dorr et al. (2021) systematically evaluated the environmental impacts of urban agriculture systems. Clerino et al. (2023), for their part, investigated for 19 case studies in France the stakeholders' approaches toward sustainability assessment in urban agriculture revealing the breadth of criteria and indicators evaluated. They differentiated 10 themes of sustainability and 3 clusters of urban agriculture systems. Still, as highlighted in Dorr et al. (2021), no study proposes a thorough comparison of the economic, social, and environmental sustainability of urban agriculture systems, while differentiating between different UA types.

The breadth of urban agriculture's definition namely brings along a variety of systems, as displayed in Figure 1, with potentially different implications for sustainability. Classifying urban agriculture systems to assess their sustainability in a systematic way is therefore essential. Such a classification could, in fact, help anticipate the potential sustainability trade-offs and propose preventive measures to address these.

Attempts to classify urban agriculture systems exist. Sroka et al. (2021) and Lohrberg (2016) divide urban agriculture into urban farming and urban gardening with the former being market-oriented and aiming at revenue generation

Figure 1 Illustration of the breadth of urban agriculture systems: a vertical farm on the left and an urban garden in Rapperswil on the right © Agroscope, Carole Parodi and Stefan Mann

from product sale or the provision of related services and the latter having a low market orientation, production intensity, and scale and aiming at social and civil benefits. Goldstein et al. (2016) propose a classification based on building integration and space conditioning composed of four different types of urban agriculture systems: ground-based-non-conditioned, ground-based-conditioned, building-integrated-non-conditioned, and building-integrated-conditioned. They further map different characteristics of the systems to highlight differences and facilitate the estimation of their potential environmental impacts. O'Sullivan et al. (2019) use this classification scheme to discuss how urban agriculture can contribute to the world's food production system. Aubry et al. (2017) extended this classification to better account for the climate mitigation potential of urban and peri-urban agricultural systems, but explicitly without focusing on their economic and social characteristics. Besides these two studies, Weidner et al. (2019) further mention various more socioeconomically driven classification approaches. More generally, Kozai (2019) classifies plant production systems into open fields, greenhouses and closed systems to put vertical farms and plant factories with artificial lighting into the agricultural context. Overall, these classification schemes tend to reflect only single aspects of urban agriculture systems. However, a classification of urban agriculture systems accounting simultaneously for potential social, economic, and environmental aspects could be a good way to guide the sustainable deployment of these systems. In fact, several authors call attention to the assumed sustainability of urban agriculture. Valley and Wittman (2019), for example, raise the question whether urban agriculture can help addressing issues of unequal access to food. Wielemaker et al. (2019), for their part, highlight the high fertilizer uses in urban agriculture in the Netherlands. Finally, Hawes et al. (2024) showed that the carbon footprint of food from urban agriculture is six times greater than conventional agriculture.

Acknowledging the need for such typology or classification of urban agriculture systems, Vásquez-Moreno and

Córdova (2013) linked urban agriculture systems to different archetypes of sustainable cities reflecting on their social, environmental, economic, and cultural potential benefits. Later, Opitz et al. (2016) compared urban and peri-urban agriculture systems according to their spatial, ecological, social, and economic factors differences. They did not assign these features to specific urban agriculture systems. Krikser et al. (2016), for their part, proposed the dimensions of self-supply, socio-cultural, and commercial interests to define three ideal types of urban agriculture, roughly corresponding to private gardens, community gardens, and private companies producing goods for a market. No differentiation of the technical features of these types was proposed. Despite literature being available proposing typologies of (peri-)urban agriculture systems (Vásquez-Moreno and Córdova 2013; Krikser et al. 2016; Opitz et al. 2016), we argue that an effort to integrate several sustainability characteristics and technical aspects of urban agriculture systems in one visually explicit classification scheme is still needed.

The objectives of this paper are, on the one hand, to propose a comprehensive classification scheme of urban agriculture systems reflecting their technical, social, economic, and environmental characteristics and, on the other hand, to systematically and reproducibly gather and summarize sustainability information for a broad range of urban agriculture systems according to the developed classification scheme. In addition, this study highlights the data gaps and the resulting need for research to better understand and quantify the sustainability of urban agriculture systems. Given the breadth of existing definitions of UA introduced at the beginning, we decided to use a simpler definition to keep the scope of this paper manageable, while ensuring a broad application potential of the proposed classification. Urban agriculture is hereby defined as the cultivation of plant-based food in urban areas, meaning cities and towns located in industrialized countries.

2 Materials and methods

The research was accomplished in four steps which will be described in more detail below. First, we identified existing urban agriculture systems in the literature, based on which we derived, in a second step, a preliminary classification scheme. Third, we mapped the systems in the preliminary classification scheme to conduct a sort of first validation. Fourth, we gathered and summarized information on the sustainability of these classes. These four steps eventually allowed us to evaluate how well the preliminary classification scheme accounted for the sustainability of the single systems and whether it needed adaptation.

2.1 Identification of urban agriculture systems

The aim of this step was to gain an overview of existing systems in urban agriculture. We conducted a literature review until April 2023 and based on following keyword combination inputted in Web of Science and Scopus:

TS = (("urban agriculture" OR "urban horticulture" OR "vertical farm*" OR "rooftop greenhous*" OR "plant factory" OR "sky farming" OR " integrated agriculture") AND ("review" OR “concept”)

Urban farming and urban gardening were not used in the combination since we assumed them to be used simultaneously to the term urban agriculture. In total, 498 articles were screened for abstract and title. Articles describing a review of urban agriculture system(s) with one or several sustainability dimensions evaluated were kept. The following exclusion criteria were followed:

- Evaluation of specific system parts only (e.g., light, substrates)
- Public perception/acceptance evaluation
- Evaluation of peri-urban systems, agroforestry, agroecology, or a local system not explicitly urban farming
- Investigation of the business suitability of a specific concept
- Feasibility study
- Regulation-focused
- Evaluation of contribution to food security

Overall, 84 articles were kept and read. In cases where the selected review articles calculated means of quantitative information of specific studies, we retrieved the original data from the specific case studies. This added seven papers to the total, so that 91 papers were finally read.

2.2 Building the classification scheme

Due to the large number of possible characteristics of UA (Cahya (2016), e.g., lists 54 relevant characteristics of urban agriculture), it is difficult to choose the one most relevant to summarize the sustainability of production systems. The proposed classification scheme includes production and cooperation intensity extending the taxonomy proposed by Goldstein et al. (2016). Goldstein et al. (2016) namely used environmental sustainability claims to set up a taxonomy for urban agriculture and so help direct future quantitative sustainability assessment research. Their taxonomy reflects differences in operational characteristics, capital inputs, and urban symbiosis potentials but does not mention any differences in specific social or environmental impacts.

The same aspects as listed by Goldstein et al. (2016) were used as technological starting points of our classification scheme. We kept the distinction between ground-based and building-integrated since it allowed a sufficient differentiation between the types of urban agriculture systems. However, distinguishing only between conditioned and non-conditioned systems was, in our opinion, too coarse. Kozai (2019), for example, classifies plant production systems as open, semi-closed, and closed. We therefore chose a three-level categorization to reflect the space conditioning: open systems, meaning exposed to all elements, quasi-closed systems within a very controlled environment and using artificial lighting, controlled nutrient input, controlled temperature and controlled humidity, and conditioned systems with some controlled outside inputs and others non-controlled. Examples could be partial artificial lighting or greenhouses with a filterless airflow. The urban agriculture systems can further be differentiated according to their growth-media: earthbound, airbound, or waterbound. Ground-based systems were assumed to be earthbound only. For the other categories, all three growth-media were kept as possibilities. Our technological classification therefore differentiates ground-based and building-integrated systems being either open, quasi-closed, or conditioned with a further differentiation according to the growth media.

Looking for an overarching characteristic according to which urban agriculture systems can be further grouped coherently, production intensity appeared as the most suitable parameter. In the debate around sustainable agriculture, the intensity of production has always been one of the core issues. The entire movement of organic agriculture, for example, claimed to provide more sustainability through less intensity (Niggli et al. 2007; Goh 2011; van Grinsven et al. 2015). On the input side, it has become obvious that the intensity of factor use in agricultural production processes is one of the key variables characterizing agricultural systems (Mann 2018), whereas on the output side, yield levels are often used as indicators (Ruiz-Martinez et al. 2015).

Finally, particularly in developed nations (Svendsen et al. 2012), but also in the Southern hemisphere (Asad et al. 2014), social reasons are the main motivation for many varieties of urban agriculture. Where many people live together in an urban setting, joint care for plants can be a good base for social capital formation (Kanosvamhira and Tevera 2019). While Veen et al. (2020) claim that most prosumers have a very pragmatic motivation, Ritzel et al. (2022) distinguish between the private and the commons prosumer, depending on the intensity of cooperation between the stakeholders in the system. Given the fact that building social capital is one of the main challenges in urban systems (Mpanje et al. 2018), it is certainly justified to use the intensity of cooperation as one of the variables for our classification scheme. We therefore suggest intensity of cooperation as the third measurement to include non-business relationships between participating individuals, and the resulting gain in social capital.

2.3 Mapping based on literature review

Once the classification scheme was defined, we tested whether the urban agriculture systems mentioned in the 91 articles from the literature review could be fitted in our classification scheme. This was a way to validate the proposed classification. Minor adjustments to the classification scheme were then made, mostly related to the type of substrate encountered in each urban agriculture system. The final classification system thus reflects urban farming systems found in the literature.

2.4 Sustainability of urban agriculture systems

In this fourth step, we reviewed the 91 research articles kept from Step 2.1 (see Supplementary Information, SI, for a complete list). Each urban agriculture system discussed or evaluated per study was assigned a category according to our preliminary classification scheme, and information on the substrate, environmental, social, and economic impacts were extracted. Qualitative as well as quantitative information were gathered. We gathered all sustainability information available, even if it was not reported in the form of a specific indicator. The method used for the evaluation was also captured. After screening all articles, the quantitative and qualitative information was summarized per category and sustainability dimension to draw conclusions on the sustainability of each urban agriculture category and evaluate the suitability of the classification scheme. The sustainability dimensions used here align with the definition of the United Nations given in 2002 during the World Summit on Sustainable Development and encompasses the social, economic, and environmental dimensions (United Nations 2002).

The comparison of the quantitative sustainability information available focused on the crops mentioned most in the literature. The results were taken directly from the literature without any methods, system boundary, or assumptions' harmonization. Only the units of the single impact categories were converted to a common unit using standard factors, e.g., 1 kWh = 3600 kJ. This was the best way to use the collected information despite the limited number of available studies and the lack of precise knowledge on the methodological choices behind each impact value. Accordingly, the results drawn from the quantitative comparison should be interpreted with caution, as rough trends only.

3 Results and discussion

3.1 Classification scheme and validation

Figure 2 shows the proposed classification scheme, which includes five categories of urban agriculture systems, namely, (1) building-integrated quasi-closed systems, (2)

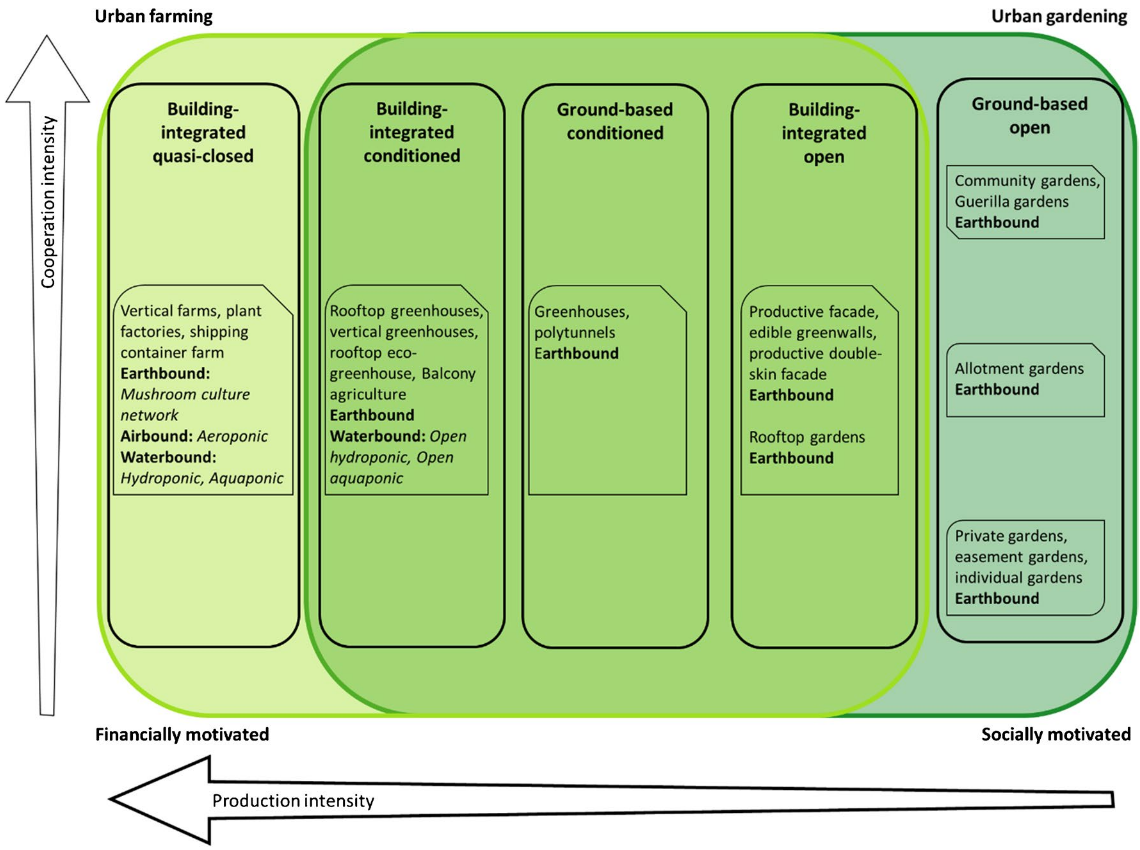

Figure 2 Proposed taxonomy of urban agriculture systems. The names in italic are examples taken from the literature. The pale green color represents urban farming systems which are rather financially motivated and the dark green color urban gardening system which are socially motivated. Systems in between have another green color coding. The words in italics were extracted from the 91 scientific articles and describe urban agricultural systems. Apart from generic terms like "conditioned agriculture" or "controlled environment agriculture," all systems could be placed in the figure

building-integrated conditioned systems, (3) ground-based conditioned systems, (4) building-integrated open systems, and (5) ground-based open systems.

Building-integrated is a synonym of building integrated agriculture, zero-acreage farming (e.g., Specht et al. (2014)), or (edible) green infrastructure (e.g., Russo and Cirella (2020); Harada and Whitlow (2020)), while ground-based systems are placed directly on the ground, with no connection to the surrounding buildings. This keyword assignment was based on the definitions found in the respective papers. Among the 91 articles read, no ground-based system in urban agriculture was reported to use any other substrate than soil. Figure 2 therefore only lists earthbound as possible substrate for this category, even though other substrates are found in ground-based systems in conventional agriculture. On the other hand, we did not find evidence for airbound systems in building-integrated conditioned nor in building-integrated open systems, and for the latter we did not find evidence of waterbound systems either. As a result, the classification scheme in Figure 2 does not list these growth-media as possibilities, even if they may occur in practice.

The clusters in Figure 2 depict, from right to left, an increasing trend in economic production intensity, synonym of higher technological complexity and market orientation and decreasing orientation toward the communities within which the systems are imbedded. We summarized this by including the keywords "socially motivated" and "financially motivated" in Figure 2. Financial motivation should here be understood as the motivation to generate income from the crop produced, not to save money by not having to buy food which can be grown in a garden. Urban gardening (right) and urban farming (left) represent the two extremes along this axis with a smooth transition between them. Building-integrated quasi-closed systems are a clear example of an urban farming system and ground-based open systems of urban gardening, but the other three systems can be either of both depending on the context. The trend in technological complexity, market-orientation, and community-orientation is therefore less pronounced over these three categories.

The classification scheme in Figure 2 further vertically differentiates the urban agriculture systems according to their cooperation intensity: low at the bottom and high at the top. While community gardening and individual gardens are very similar in terms of their low economic production intensity and therefore appear in one block on the right for the classification scheme (Figure 2), they differ in terms of cooperation intensity. Community gardens have a high cooperation intensity and appear at the top right of the classification scheme, and private garden at the bottom right, since the cooperation intensity is limited. Such a differentiation did not appear from our review for the other urban agriculture classes so that all other urban agriculture systems were placed in the middle of this vertical axis. Still, a separate search showed very recent examples of collaborative rooftop gardens (Better Building Partnership 2024; UMass Lowell 2021), as well as guides for community-supported agriculture (CSA) systems using building-integrated quasi-closed systems (Growcer 2024). This further supports the inclusion of cooperation intensity as a characteristic in the classification scheme.

The words in italics in Figure 2 were extracted from the 91 scientific articles and describe urban agricultural systems. Apart from generic terms like "conditioned agriculture" or "controlled environment agriculture," there was no system that could not be placed in Figure 2.

Different crops can be grown in the single urban agricultural systems categories mentioned in the reviewed literature, as presented in the SI. The largest variability of crops is found in ground-based open systems (19), and least examples were available for ground-based conditioned (5). Building-integrated quasi-closed systems are particularly well suited for leafy vegetables, but research is ongoing to broaden this range to root crops or potatoes (Hardy et al. 2018).

3.2 Sustainability of urban agriculture categories

Overall, quantitative and qualitative information was available in 49 out of the 91 studies reviewed, listed in the SI for each urban agriculture category. Overall, information was available in 30 studies for building-integrated quasi-closed systems, 11 for building-integrated conditioned, 9 for ground-based conditioned, 4 for building-integrated open, and 15 for ground-based open. Specifically, 30 studies investigated the sustainability of building-integrated quasi-closed systems, 11 for building-integrated conditioned, 9 for ground-based conditioned, 4 for building-integrated open, and 15 for ground-based open, while only 1 study could include information on different urban agriculture categories. The categorization of each study in a specific urban agriculture category was made case-by-case depending on the system described in the studied paper. Each study reported qualitatively or quantitatively different type of sustainability information (Figure 3).

The large number of studies for building-integrated quasi-closed UA systems reflects the current focus of the sustainability research on technologically complex systems. Figure 3 also clearly highlights the lack of quantitative research in the sustainability assessment of urban agriculture, especially for social impact assessment. Overall, 16 out of the 21 studies investigating social sustainability of urban agriculture systems were a form of literature review, while the other research articles used perception studies, observations, or interviews with experts or workers. The only quantitative information is a ranking conducted by the interviewees about their gardens. This is probably due to the fact that

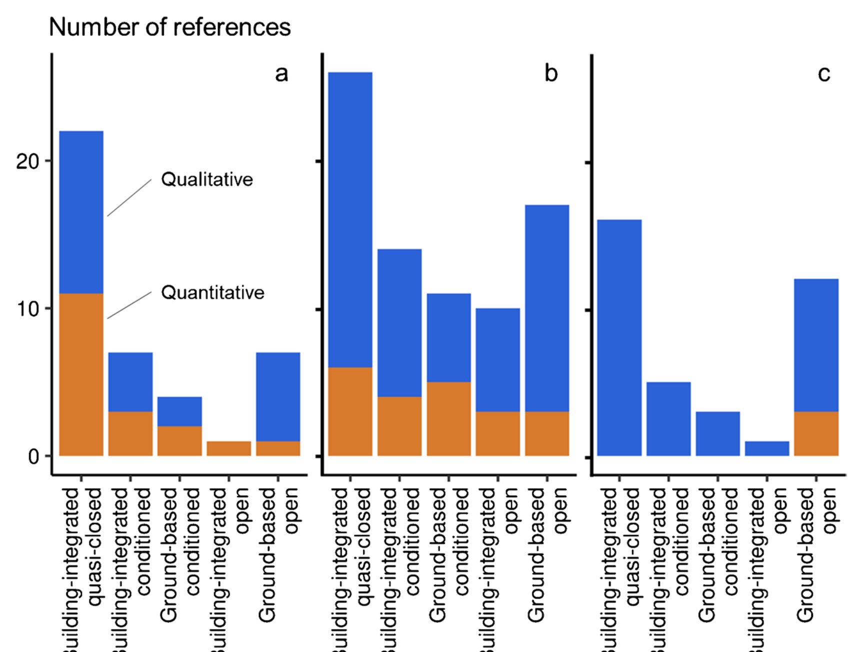

Figure 3 Number of references reporting quantitative and qualitative sustainability information from the 49 studies providing such information per urban agriculture type. **a** Economic sustainability, **b** environmental sustainability, and **c** social sustainability.

most of the established indicators of social sustainability in agriculture are tailored either to plantations (Desiderio et al. 2022) or family farms (Janker et al. 2019). While qualitative information is valuable since the related indicators are often easier to implement and comprehend, can allow better stakeholder inclusion (Clerino et al. 2023), and consideration of positive impacts such as ecosystem services (Sanyé-Mengual et al. 2020; Giacchè et al. 2021), they suffer from more potential bias, are less easily reproduced and compared to other studies (Queirós et al. 2017). The lack of quantitative information for the social dimension as well as the lack of a harmonization of the information to be provided implies limited evidence about the different intensity of social sustainability.

For the environmental dimension of sustainability, Figure 3 reveals that more quantitative evidence is available. Out of the 44 reviews reporting environmental impacts of urban agriculture systems, 31 relied on literature data, 2 focused on literature data from life cycle assessments (LCA), 4 used life cycle assessment directly, 2 used an energy optimization model, 2 a questionnaire, 1 implemented a perception study with experts, and the rest carried out an accounting of CO_2-equivalents or energy use. Overall, the representativeness and robustness of the single reviews were variable: Some statements were made based on several congruent sources, others only using one or two sources.

For the economic information, the situation is somewhere between the two others. While quantitative information exists, it is extremely diverse and not applied in a uniform, comparable manner. One study relied on a life cycle costing and published quantitative results for five different indicators found in no other review, namely the capital expenditures, net present value, internal rate of return, benefit to cost ratio, return on investment (Liaros et al. 2016).

3.2.1 Qualitative evaluation of the sustainability of urban agriculture systems

Figure 4 summarizes per urban agriculture category and sustainability dimension the three keywords occurring the most, and at least twice, in the gathered literature. The differentiation between the urban agriculture systems was kept on the production intensity level since the gathered literature made a refinement according to the cooperation intensity difficult.

Here too, the lack of studies on the social impact of urban agriculture systems is obvious. Still, it is interesting to note the change in the social impacts assessed depending on the urban agriculture category: Education- and community-related impacts are on the right of the scheme, meaning toward urban gardening, while employment and food security are on the left toward urban farming. Economic keywords about profitability are important over the entire classification scheme. The environmental impacts considered do not vary much depending on the urban agriculture category and include energy input, water use, and global warming potential. Biodiversity is an important topic for ground-based open systems, which is less cited for other urban agriculture systems.

The keywords listed in Figure 4 often appear in the reviewed studies as part of qualitative claims on the sustainability of urban agriculture systems. These claims are sentences related to the urban agriculture systems, supported or not by findings or references, found in the literature. We found a list of similar claims stated in at least three different reviewed studies for building-integrated quasi-closed systems and ground-based open systems and list them in Table 1 per sustainability dimension. These systems correspond to the ones studied the most in the reviewed papers (Figure 3). A recent study showed that the carbon footprint of food from urban agriculture, collective gardens, urban farms, and individual gardens was six times greater than conventional agriculture (Hawes et al. 2024). This further highlights the necessity to carefully reflect on the claims made in the literature, especially if they are not explicitly supported by literature or findings.

3.2.2 Quantitative evaluation of the sustainability of urban agriculture systems

Figure 5 displays environmental and economic information for two crops, lettuce and tomato, and all five urban agriculture systems. The focus is on lettuce and tomato because they were mentioned most in the literature. As mentioned in the methods Section 2.4, the results presented in Figure 5 should be interpreted with caution as rough trends only. We discuss the usefulness of this approach at the end of the section.

One trend derived from Figure 5 is that the production of lettuce is more energy intensive in building-integrated quasi-closed or conditioned systems than the other classes of urban agriculture systems. Lettuce produced in ground-based conditioned systems, on the other hand, requires the least energy per kg produced compared to all systems. It is difficult to derive a similar trend for tomato production, since the energy requirement when cultivated on ground-based conditioned systems varies over one order of magnitude. The variability in global warming potential across and per crop type also ranges over several orders of magnitude making any trend identification difficult. The information on water use gathered in literature displays a higher water use for tomato production on ground-based open systems compared with building-integrated quasi-closed systems, and at a same time a decreasing yield. The lower yield for ground-based open compared with building-integrated quasi-closed systems seems to apply for lettuce production too. The difference in impacts between the crop types highlights the

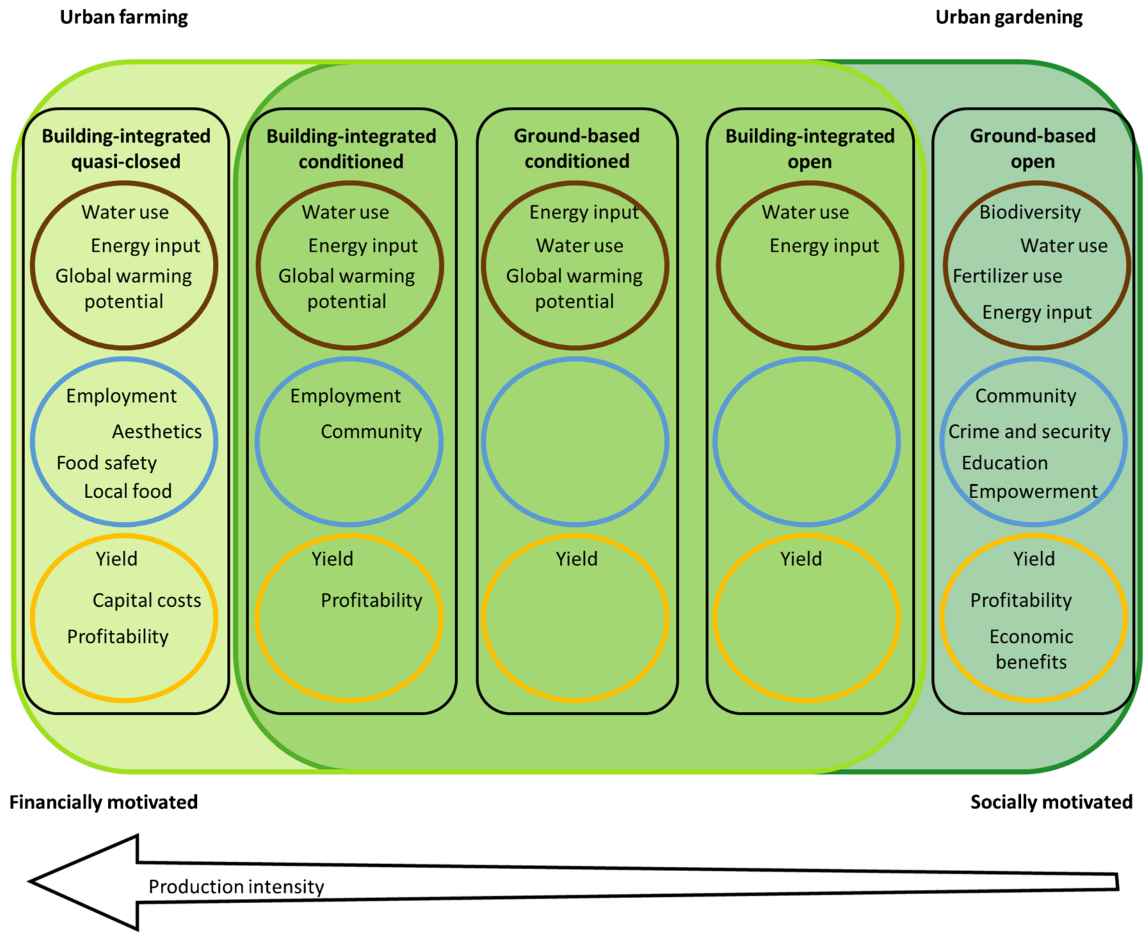

Figure 4 Three most occurring keywords (occurring at least in two studies) in the reviewed papers per urban agricultural systems taxonomic group and sustainability dimension. Lists of more than three keywords mean that the keywords were occurring the same number of times. The colors of the circles represent a different sustainability dimension: brown for the environmental, blue for the social, and orange for the economic dimension.

importance of differentiating sustainability results for urban agricultural systems by crops.

Another factor potentially affecting the results' variation and not shown in Figure 5 are spatial characteristics. The information was not available for all studies, but Benis et al. (2017) show that while yield can be held relatively constant across countries for tomatoes grown in building-integrated quasi-closed systems (10% variation), the resulting water use, energy input, and global warming potential can be up to three times higher depending on the location. Seasonality is therefore another important aspect to consider when reporting sustainability results of urban agriculture systems.

Seasonality and methodological choices such as system boundaries can further explain the large variability in the results displayed in Figure 5. In urban food systems, the transport up to the consumer can namely represent 6% of the climate change impacts (Stelwagen et al. 2021). Further, exemplarily, Bell and Horvath (2020) showed that "out-of-season" oranges could have an up to 50% higher carbon footprint than in season oranges in the USA.

Comparing Figure 5 with available literature allows us to reflect on the presented results. Hawes et al. (2024) compared the extend and variability of the climate change impact of low-tech urban agriculture, corresponding to building-integrated and ground-based open systems in our classification, to conventional agriculture. The ratio between the maximum and the minimum climate change impact of building-integrated and ground-based open systems they calculated was around 5 for tomatoes and 2 for lettuce, slightly higher than in Figure 5 (12 and 5 respectively). The comparison with the extensive systematic review of Dorr et al. (2021) highlights that some values found in literature for the sustainability information shown in Figure 5 might have been obtained under particularly favorable conditions (very high yield) or on the contrary unfavorable conditions or have included additional life cycle stages (very high global warming potential or water use). However, a direct comparison

Table 1 Claims made from literature available in building-integrated quasi-closed systems and ground-based open systems

Sustainability dimension	Urban agriculture systems	Claims made in the literature	Citing literature
Environmental sustainability	Building-integrated quasi-closed systems	Lower water use than traditional farming	(Bunge et al. 2022; Folta 2019; Gómez et al. 2019; Shamshiri et al. 2018; Van Delden et al. 2021)
		Lower land use requirements than traditional farming	(Al-Kodmany 2018; Bunge et al. 2022; Gonnella and Renna 2021; Saad et al. 2021; Van
		Efficient fertilizer use	(Al-Kodmany 2018; Engler and Krarti 2021; Gómez et al. 2019; Van Delden et al. 2021)
		Lower pesticide use than traditional farming	(Al-Kodmany 2018; Saad et al. 2021; Van Delden et al. 2021)
		High energy use	(Gómez et al. 2019; Mohareb et al. 2017; Oh and Lu 2022; Saad et al. 2021; Van Delden et al. 2021)
	Ground-based open systems	Efficient fertilizer use	(Goldstein et al. 2016; Rusciano et al. 2018; Taylor and Lovell 2014)
		Varying impact on biodiversity	(Clucas et al. 2018; Royer et al. 2023; Sartison and Artmann 2020; Taylor and Lovell 2014)
Social sustainability	Building-integrated quasi-closed systems	Local jobs created	(Benis and Ferrão 2018; Folta 2019; Gonnella and Renna 2021; Saad et al. 2021; Shamshiri et al. 2018; Van Delden et al. 2021)
		Positive connotation for aesthetics/cultural heritage	(Gómez et al. 2019; Saad et al. 2021; Van Delden et al. 2021)
		Potentially improved food safety	(Folta 2019; Saad et al. 2021; Van Delden et al. 2021)
	Ground-based open systems	Positive impact on education (in general or related to nutrition or the environment)	(Eigenbrod and Gruda 2015; Ilieva et al. 2022; Laycock Pedersen and Robinson 2018; Sartison and Artmann 2020)
		Increased food safety	(Eigenbrod and Gruda 2015; Ilieva et al. 2022; Taylor and Lovell 2014)
		Improved social bonds	(Ilieva et al. 2022; Rusciano et al. 2018; Säumel et al. 2019)
		Contribution to empowerment	(Ilieva et al. 2022; Sartison and Artmann 2020; Taylor and Lovell 2014)
		Help creating sense of community	(Eigenbrod and Gruda 2015; Goldstein et al. 2016; Ilieva et al. 2022; Laycock Pedersen and Robinson 2018; Rusciano et al. 2018; Sartison and Artmann 2020; Taylor and Lovell 2014)
		Contribute to reducing crime and security related costs	(Eigenbrod and Gruda 2015; Ilieva et al. 2022; Laycock Pedersen and Robinson 2018; Sartison and Artmann 2020; Säumel et al. 2019)
Economic sustainability	Building-integrated quasi-closed systems	Diverging statements on profitability	(Bunge et al. 2022; Oh and Lu 2022; Van Delden et al. 2021; Weidner et al. 2019)
		Considerable capital costs	(Benis and Ferrão 2018; Folta 2019; Oh and Lu 2022)
		Increased yield	(Al-Kodmany 2018; Bunge et al. 2022; Gonnella and Renna 2021; Oh and Lu 2022; Saad et al. 2021; Shamshiri et al. 2018)
	Ground-based open systems	Can lead to savings	(Ilieva et al. 2022; Rusciano et al. 2018; Taylor and Lovell 2014)

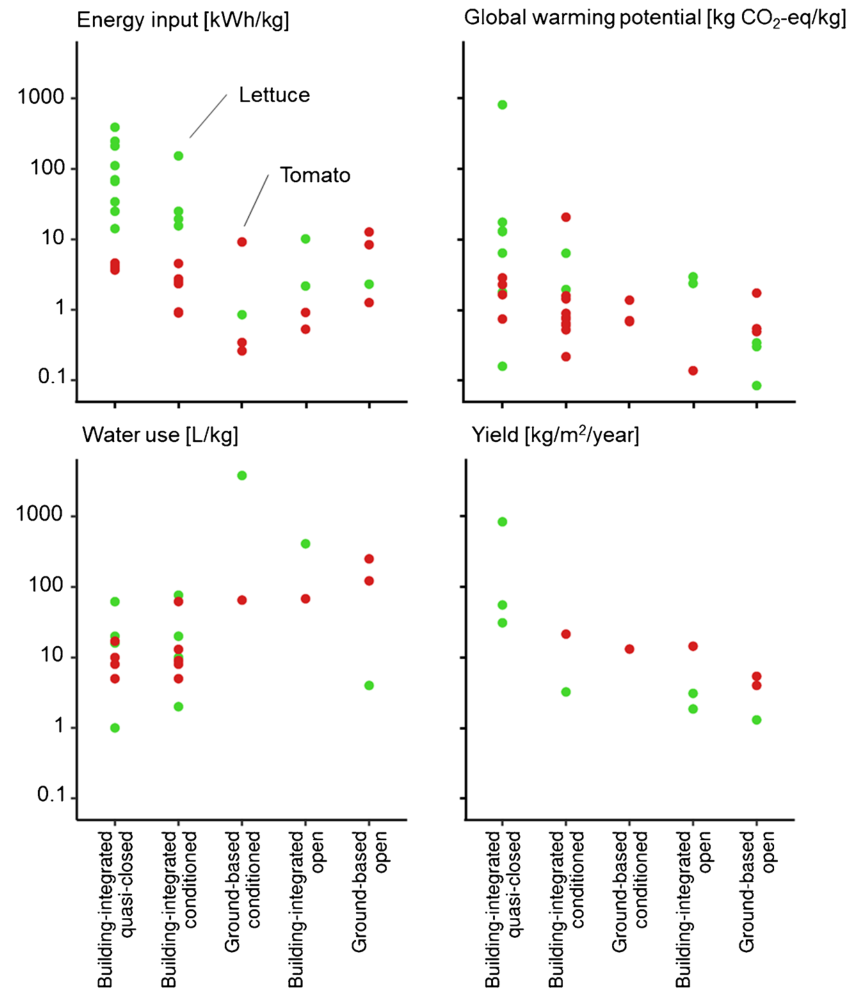

Figure 5 Environmental and economic impacts of the five urban agriculture systems differentiated for two crops (lettuce and tomato). The scale is a 10-logarithmic scale; the impacts are per kg of crop produced (Orsini et al. 2020b; Avgoustaki and Xydis 2020; Weidner et al. 2019; Dorr et al. 2021; O'Sullivan et al. 2019; Kozai 2019; Rothwell et al. 2016; Shahda and Megahed 2023; Meng et al. 2023; Kulak et al. 2013; Sanyé-Mengual et al. 2015; Benis et al. 2017; Forchino et al. 2018; Kuswardhani et al. 2013; Hatirli et al. 2006).

is difficult given the different categorization of urban agriculture systems. Another possible explanation could be that some of the systems analyzed were not yet fully operational or in the early stages of production and that economies of scale play a role. Despite the lack of harmonization of the results, driven by the aim to include as many data points as possible, Figure 5 is useful to get a first sense of quantitative differences between the sustainability of the five urban agriculture classes proposed here. In addition, a need for further research can be derived from this in order to further investigate the influencing factors and the inherent differences of the systems as well as the methodological differences of the studies.

3.3 Matching sustainability and technical classification criteria

The classification scheme proposed foresees five urban agriculture classes. It was built by accounting for technical aspects, namely building integration, space conditioning, and urban agriculture systems, as well as socioeconomic considerations, namely the production and cooperation intensity. The characteristic linked to cooperation intensity allowed differentiating mostly urban gardening and less urban farming systems potentially questioning its usefulness. Still, differentiating urban agriculture systems according to the cooperation intensity reflects an essential part of the social dimension of sustainability. Several publications namely stress the positive social impact of urban gardens apparently fostering cooperation, without nuancing that this statement applies only for community gardens and not, for example, private gardens (Säumel et al. 2019; Rusciano et al. 2018). Laycock Pedersen and Robinson (2018) and Rogge et al. (2018), for their part, clearly address the community benefit of community gardens, further supporting the importance of including cooperation intensity as a separate characteristic for classifying urban agriculture systems. Further, Hawes et al. (2024) showed lower climate change impact of urban farms, corresponding to ground-based open systems with low collaboration intensity compared with urban collective gardens, corresponding to ground-based open systems with high collaboration intensity.

Compared with currently available classification systems presented in the introduction, the classification scheme proposed here allows to integrate technical as well as economic and social considerations to compare different urban agriculture systems. This framework also has the advantage of visually representing the spectrum of urban agriculture systems with concrete examples of existing systems. Still, its validity needs to be further tested as new urban agriculture systems or more information on the sustainability of existing urban agriculture systems becomes available.

The qualitative statements on the social impact for the categories further supported the distinction between urban farming and urban gardening systems. The sense of community developed and educational potential of urban gardens were prominently mentioned, as opposed to the potential for job creation and food safety support for urban farms. A further support for this horizontal division of urban agriculture systems was given by the qualitative statements on the environmental dimension. In fact, these statements discussed more extensively the potential contribution of ground-based open systems to biodiversity, while savings in water and energy use were more central to qualitative statements on building-integrated quasi-closed systems.

Overall, a trend toward less energy input and lower yields for ground-based open systems compared to building-integrated quasi-closed systems appears from the quantitative comparison, supporting even further the horizontal axis of the classification scheme. However, the limited number of quantitative sustainability information available; the large range between the results caused by geographical, seasonal, and methodological variations; and the mere lack of quantitative information for the social dimension limit the further use of the quantitative comparison as support of the proposed scheme, especially for the vertical axis. Despite these findings being rather supportive of the proposed classification scheme and its three characteristics, additional quantitative studies or more detailed qualitative evaluations are necessary to further underpin the usefulness of the proposed scheme.

Quantitative sustainability evaluations of urban agriculture systems, especially in the middle of the spectrum of our proposed classification scheme, are therefore needed. In addition, the potential of urban agriculture systems to reuse waste streams and its implication on the sustainability of these systems should be evaluated. Some studies namely argue that such circularity contributes to the sustainability of urban agriculture systems (Bennedetti et al. 2023; Nowysz et al. 2022).

4 Conclusion

In an attempt to better understand the sustainability of urban agriculture systems, we first proposed a classification scheme of urban agriculture systems. Besides technical characteristics, the intensity of production and the intensity of cooperation were two additional characteristics allowing a distinction between different food production systems in cities. This is a major novelty of our work since most existing classification schemes do not include three dimensions. Assigning the sustainability claims and evaluations found in literature to these different classes supported the usefulness of our classification scheme since they aligned well with the suggested characteristics. At one end of the scheme, urban gardens were associated with educational potentials, biodiversity improvements, and lower yields, while at the other end, urban farms were mostly linked to job creation, food safety, water savings, and higher yields. Another result highlighted the importance of carefully interpreting and using sustainability claims of urban production intensive systems, such as vertical farms. Scientific evidence so far does namely not clearly demonstrate an increased sustainability of these systems compared with other urban agriculture systems. The proposed classification scheme is a first attempt to roughly evaluate sustainability claims around urban agricultural systems. We also showed the importance of quantitative environmental and economic sustainability results as well as robust and comparable social sustainability evaluations to anticipate potential sustainability trade-offs for a single urban agricultural system or between different system types. Such information can namely contribute to ensuring the sustainable deployment of such systems.

In order to provide clearer evidence of the sustainability of urban agriculture systems in general, we identified two main future research areas. First, the application of life cycle assessment (LCA) for the evaluation of the environmental sustainability of urban agricultural systems following set guidelines for the methodological choices could help ensure comparability between studies and potentially reduce the differences in environmental sustainability results of urban farming systems. Second, defining standardized indicators, particularly quantitative ones, to describe the socioeconomic sustainability dimension is essential to increase evidence on the socioeconomic sustainability of urban agricultural systems.

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Code availability Not applicable

Declarations

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Consent to participate Not applicable

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