9
COLLANA DEL DIPARTIMENTO DI ECONOMIA AZIENDALE

A cura di

MARIA CLAUDIA LUCCHETTI, MARIA FRANCESCA RENZI

QUALITÀ, INNOVAZIONE E SOSTENIBILITÀ NELLA FILIERA AGRO-ALIMENTARE

Il contributo delle Scienze Merceologiche

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Indice

Life cycle assessment of soilless systems: a systematic literature review

Antonio Licastro
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Abstract (ENG)
Soilless systems imply the use of substrates instead of soil and delivering nutrients through liquid mixtures, leading to water and fertilizer reduction. In addition, being in a controlled-environment, harmful substances like pesticides are minimized. However, the complexity of these systems requires comprehensive assessments to avoid unintended negative environmental impacts. By conducting a systematic review of 46 Life Cycle Assessment (LCA) articles on soilless systems, this study examines methodological choices and assumptions made by LCA practitioners, shedding light on the strengths and limitations of current practices. Results show that mass-related functional units and cradle-to-gate system boundaries are predominant in the assessed studies, reflecting a focus on production stage, while distribution and consumption phases often receive less attention. Environmental hotspots identified include energy consumption for irrigation and heating, nutrient solution, and structural materials. Notably, the impacts associated with macro-nutrients, as well as steel, aluminum, polyethylene from greenhouse structure, and non-renewable energy sources, have been found to be significant in terms of environmental impacts. The use of recycled materials for infrastructure, the integration of renewable energy sources such as wind power or photovoltaic system, and the optimization of fertilizer or use of biofertilizer, may minimize the environmental impacts of soilless systems. By adopting a life cycle perspective and incorporating sustainable practices, soilless systems can play a vital role in achieving environmentally friendly and resource-efficient agriculture.

Keywords: soilless; systematic review; life cycle assessment; LCA; environmental sustainability

1 Introduction

The last 50 years witnessed a surge in agricultural yield per hectare allowing better access to food and reducing hunger for many individuals. However, this commendable progress has come at a considerable environmental cost (Pingali, 2012). Chemical compounds contribute to exacerbate of aquatic and terrestrial eutrophication and acidification, while less then optimal approaches to soil and water management, coupled with inefficiencies in the disposal of agricultural waste led to decrease in soil fertility and increase in soil contamination, water depletion, greenhouse gas (GHG) emissions, and deforestation (Popp *et al.*, 2014; Clark and Tilman, 2017; Searchinger *et al.*, 2018; Casey *et al.*, 2022). As World population is expected to grow up to 8.5 billion (FAO, 2021), there are concerns that the increasing food demand may further intensify the environmental pressure on agricultural production.

Nonetheless, in response to these challenges, the surge of environmental awareness has prompted the exploration for more sustainable practices. One promising approach is the implementation of Urban Agriculture (UA) by relocating a portion of agricultural production in urban spaces (Payen *et al.*, 2022). In doing so, UA not only addresses food security concerns, but also environmental ones (Orsini *et al.*, 2013; Pradhan *et al.*, 2020). Indeed, by reducing the land use of traditional agriculture, UA offers opportunity for nature to reclaim its space, fostering the restoration of natural ecosystems (Nicholls *et al.*, 2020), as well as it helps to preserve biodiversity (Clucas, Parker and Feldpausch-Parker, 2018), improve social cohesion (Park *et al.*, 2019) and mitigate urban heat island (Oberndorfer *et al.*, 2007). Urban food production can take place in grey spaces like ground-based urban land, existing buildings, façades or rooftops, as well as in green spaces, like gardens or parks (Payen *et al.*, 2022). Furthermore, UA encompasses various sub-categories, such as the orientation of farming (vertical or horizontal), the choice of growth medium, and the degree of environmental control during crop cultivation (Payen *et al.*, 2022).

However, UA practices are not exempt from challenges, as open-air, ground-based, and horizontal urban farming systems appear to be susceptible to contamination stemming from heavy metal emissions originating from industrial and urban sources (Mok *et al.*, 2014). Additionally, they are exposed to the presence of soil-borne pathogens, viruses, and fungi, which not only jeopardize crop health but also pose risks to human well-being (Salomon *et al.*, 2022).

In view of these shortcomings, a strategic move would be to employ Controlled Environmental Agriculture (CEA) practices. Thus, plants can grow unharmed by pests nor diseases within a well optimized environment

(Casey *et al.*, 2022). Soilless systems are typically employed in CEA having the main advantage of eliminating the need for soil altogether. Instead, crops are grown in specially formulated nutrient solutions or solid substrates (inert or organic), providing optimal conditions for plant growth while minimizing environmental impacts (Gonnella and Renna, 2021). The term "soilless" is often used as a synonym of "hydroponics" (formed by the Greek words for "work" and "water"), however some authors argue that the term hydroponics should refer strictly to systems where plants grow in liquid substrates (Gericke, 1937; Adams, 2002) while others use them interchangeably (Savvas and Gruda, 2018; Fussy and Papenbrock, 2022). Hence the preferred term for this article is "soilless".

While particularly well-suited for urban agriculture (Arcas-Pilz *et al.*, 2021), soilless systems can also be employed in rural settings (Anton *et al.*, 2005; Maaoui *et al.*, 2021). Soilless systems also can be easily integrated with cutting-edge technologies such as automated irrigation combined with remote monitoring, and sensors, facilitating precise manipulation of climate and plant parameters, thus optimizing resource use (Massa *et al.*, 2020; Gonnella and Renna, 2021). However, some authors contend that the incorporation of advanced technologies may result in making these systems into energy-demanding ones (Kikuchi *et al.*, 2018; Casey *et al.*, 2022), potentially negating the environmental improvements they initially provided (Rothwell *et al.*, 2016). In addition, if on one hand certain inert substrate media (perlite or rockwool) possess relevant physical properties, like good water retention (Raviv *et al.*, 2002), on the other their environmental and social impacts across their life cycle remain relevant (Vinci and Rapa, 2019; Toboso-Chavero *et al.*, 2021). Furthermore, fertigation management approaches used in soilless system presents certain environmental consequences, such the case of open-loop systems, where effluents are not recycled (like in closed-loop ones), rather disposed into the environment contributing to eutrophication (Torrellas *et al.*, 2012). Other aspects to take into consideration are the climatic conditions, as system operating in colder regions may require additional energy for heating the crops, leading to unwanted environmental impacts (Goldstein *et al.*, 2016).

Given the many features these systems can have, it appears compelling the use of comprehensive methods to assess their environmental impacts (Dsouza *et al.*, 2021). Studies on soilless systems have primarily focused on specific processes through experimental trials, often without considering the system as a whole or encompassing all relevant aspects (Armanda *et al.*, 2019). Some experimental studies (Figueiredo, Sala and Souza, 2021; Dutta *et al.*, 2023) have showed that soilless systems can lead to reduced water and fertilizer consumption compared to conventional systems, implying potentially lower environmental impacts. However, it is important to note that these impacts are inferred from experimental results and have not been quantitatively measured and assessed. Recent reviews on environmental impacts of soilless systems mentioned Life Cycle Assessment (LCA) as a valuable method to assess their impact, by thanking a life-cycle perspective (Barrett *et al.*, 2016; Gruda, Bisbis and Tanny, 2019; Fussy and Papenbrock, 2022). Indeed, LCA allows the identification and then the quantification of the potential environmental impacts across a system's (i.e., product, process, or service) life cycle stages (ISO 2006a; ISO 2006b). Despite being one among many others environmental impact assessment methods available (Beloin-Saint-Pierre *et al.*, 2017), LCA is the sole method which take a life-cycle approach. Furthermore, when evaluating environmental impacts, it's important to recognize that results can vary significantly depending on the chosen method and how that method is implemented. This highlights the need for careful consideration of methodological choices in environmental assessments.

In this contest, the goal of this study is to carry out a literature review of environmental assessment studies applied to soilless systems, in order to point out the methodological choices and to highlight the potential environmental impacts of these systems.

2 Methodology

The research methodology used to systematically select the relevant articles was preceded by two preliminary steps to prepare the literature review.

First, an overview of literature was conducted to identify the nomenclature of soilless systems and to provide a clear description of the diverse methods being under the umbrella definition of "soilless systems": this allowed identifying the terms to be used in the search strategy. The terms identified through the literature overview are reported in Table 1, according to the type of growing medium.

Type of growing medium	Nomenclature
Liquid medium	Drip Irrigation Hydroponics
	Deep-water culture (DWC) (or deep flow technique or floating technique or floating raft or floating system)
	Nutrient Film Technique (NFT)
	Aeroponics
	Fogponics or Atmoponics
	Flood and drain (or ebb and flow)
	Rotary hydroponic garden
	Root dipping technique
	Passive sub-irrigation (Capillary action technique, Kratky method and Wick technique)
	Run-to-waste
Solid medium	Hanging bag technique (or verti-grow technique)
	Grow bag Technique
	Trench technique
	Pot technique

Table 1 – Soilless techniques identified for the search strategy and classified by growing medium type

The second preliminary step involved a review-of-reviews of environmental impact assessment methods to understand which are the most used among the scientific community: this allowed to select which one to be taken in consideration in the search strategy. Hence the review of reviews has been conducted by selecting review studies, in English, that addressed at least one environmental impact assessment methods. Using Scopus and Web of Science (WoS) Database were initially identified 38 reviews, specifically 17 for WoS and 21 for Scopus. After removing duplicates (13), non-accessible articles (1), and out of the selection criteria (4), the final sample included 20 reviews. LCA was selected as the most used environmental assessment method since it appeared in 95% of the investigated reviews (figure 1).

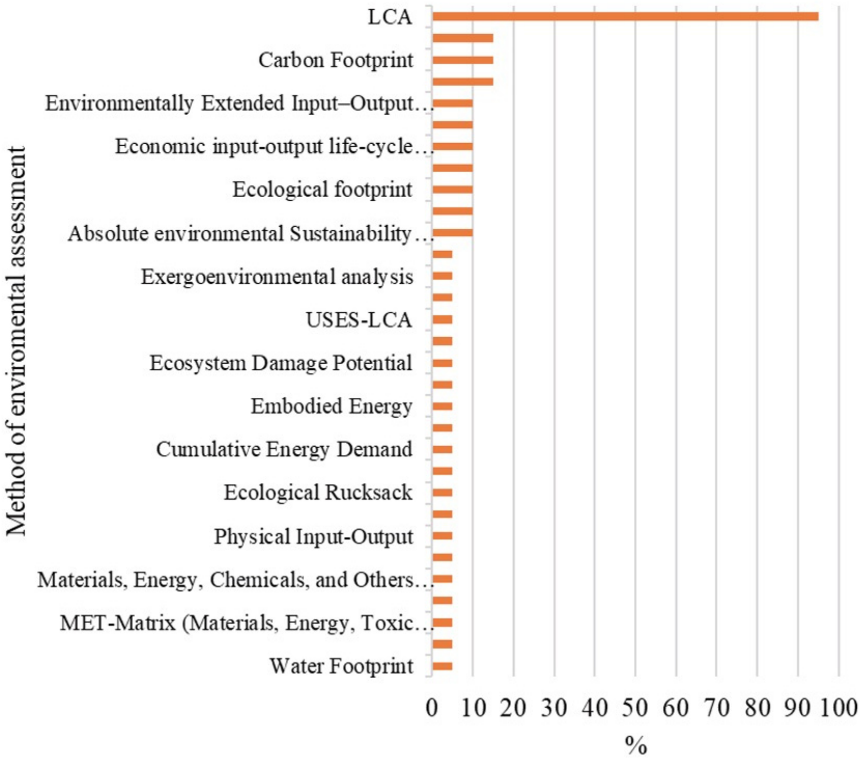

Figure 1 – Percentage frequencies of the environmental assessment methods found in the selected reviews

After these two preliminary steps, the systematic selection of LCA studies applied to soilless systems was therefore constructed by combining the nomenclature of the techniques previously identified with the keywords "LCA" or "Life Cycle Assessment". Then the search query was run in both Scopus and WoS. Articles had to be in English with a focus on the assessment of soilless systems via LCA. Reviews, conference articles, books and proceedings were excluded. The data collection process commenced in January 2023, guided by the updated version of the PRISMA protocols (Page *et al.*, 2021). The initial sample was a combined total of 139 articles, with 70 articles identified in Scopus and 69 in WoS. Following the removal of duplicates, a set of 31 articles emerged from the initial screening process. In addition, to enhance the comprehensiveness of the sample, the snowball method was employed (Wohlin, 2014), leading to the inclusion of 15 additional articles. Consequently, the final sample encompassed a total of 46 articles. Relevant data on LCA methodological choices (such as Functional Unit, System Boundaries, Goal of the study) and identification of potential hotspots were extracted implementing the FLAVIA-LCT framework (Gulotta *et al.*, 2023), and gathered in an Excel spreadsheet.

3 Results and Discussion

Most of the investigated LCA studies (33) were both hotspots and comparative analyses (e.g., Corcelli *et al.*, 2019; Blom *et al.*, 2022; Casey *et al.*, 2022), 10 were hotspots analyses (e.g., Dias *et al.*, 2017; Ghasemi-Mobtaker *et al.*, 2022) and 2 were comparative (Muñoz *et al.*, 2008; Llorach-Massana *et al.*, 2016). All followed an attributional approach, except one which followed a consequential approach (Goldstein *et al.*, 2016), as shown in figure 2. The majority of studies focused on assessing one or more farming systems with the inclusion of infrastructure and crop production altogether. For instance, comparison involved farms integrated into buildings versus ground-based ones (Goldstein *et al.*, 2016), in-soil systems vs soilless (Ilari *et al.*, 2021), open-field cultivation vs in-soil greenhouse cultivation vs soilless greenhouse (Ntinas *et al.*, 2017). While other studies gave attention also to specific greenhouse structures (rooftop greenhouse, vertical farms, plant factories, etc.), fertilization method, substrates, or heating systems. Two articles focused on methodological aspects like the definition of characterization factors or computation of N2O emissions (Antón *et al.*, 2014; Llorach-Massana, Muñoz, *et al.*, 2017). It should be noted that one article may have multiple goals.

Such concentration of objectives around production and infrastructure somehow anticipates what could be the environmental hotspots, as attention is given to nutritional solutions, heating systems, structure of greenhouse and auxiliary equipment. In addition, while attributional LCA allows decision-makers to see the current state of a system, the overwhelming use of this approach surges the need to flank it with consequential LCAs, which would enable a deeper understanding of the potential repercussions associated with the expected widespread implementation of soilless systems, thus providing decision-makers with a more comprehensive and forward-looking assessment.

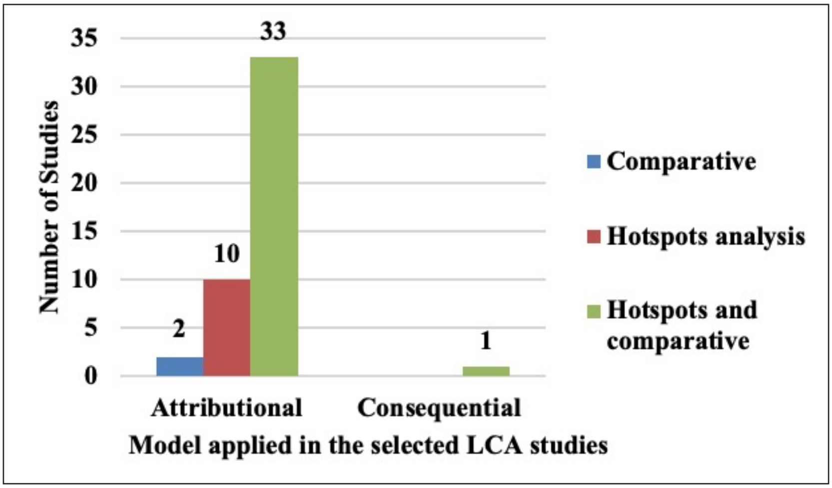

Figure 2 – Model applied in the selected papers per type of assessment

Regarding the functional unit and system boundaries, results are summarized in figure 3, where the number of detected FUs are counted per their respective system boundaries and, also in this case, one LCA study may be performed within multiple system boundaries with multiple FUs, thus in the figure is reported the number of appearances. Mass-related FU, expressed in tons or kg is the most preferred one, as it has been chosen 36 times. Surface related FU (square meter, hectare, or acre) appeared 9 times, while volume-related FU was chosen to assess the impact of substrates just two times. In addition, unit-related FU (in this specific instance, number of plants), as well as combined FU (e.g., square meter per year or kg per year) were chosen 3 times, while energy-related (in kcal) and monetary FU (€) were found 1 time. Lastly, even if in two instances (Llorach-Massana et al., 2017a; Llorach-Massana et al., 2017b) the FU was not clearly specified, it should be noted that one considered emissions only from the production phase (defined as operation phase in the article) and the other is a methodological article. Figure 3 shows that Mass-related and Surface-related FUs are employed mostly along with a cradle-to-gate approach. This, may reflect a focus on production, possibly indicating where the hotspots might lie. In addition, the use of multiple FU for the assessment of the same system can be useful for completer results, as in the selected sample only five articles used multiple FUs in their analyses. Indeed, limiting the assessment to using one type of FU may preclude the possibility to see the picture from different prospectives (Notarnicola *et al.*, 2015).

Cradle-to-gate approach dominates the sample as the main phases accounted for are raw material extraction, infrastructure (which can be integrated with its construction and maintenance), production and waste management of production waste and disposal of infrastructure. Infrastructure may include the greenhouse structure and the auxiliary equipment (irrigation system, heating system, ventilation, sensors, etc.). Most of the system boundaries are concentrated within the main two phases of soilless production: infrastructure and production. Cradle-to-grave approach is found to be chosen most when emissions from the infrastructure life cycle are accounted. For instance, one article (Blom *et al.*, 2022) accounted end-of-life emissions of the materials of the farm including only the transportation of the materials to a treatment site but not the process of material recycling, while emissions from consumption phase were included taking into account only food losses during consumption with the exclusion of energy from consumer home refrigeration and inputs needed for the food supply chain like on-site refrigeration. However in one article (Page et al., 2012), which followed a cradle-to-consumer approach, production of vehicles used for shopping trip and electricity used by consumers' refrigerator were also taken into account. Cradle-to-distribution approaches occur 10 times where in some articles (Almeida *et al.*, 2014; Goldstein *et al.*, 2016; Rothwell *et al.*, 2016; Maaoui *et al.*, 2021; Blom *et al.*, 2022; Casey *et al.*, 2022) implies the transport from farm gate to the distribution center, while, in other articles (Sanyé-Mengual, Oliver-Solà, *et al.*, 2015; Llorach-Massana, Muñoz, *et al.*, 2017; Martin and Molin, 2019), it implies the transportation from farm gate to retail. One article (Sanyé-Mengual *et al.*, 2013) compared rural farms versus urban farms and included transportation only from rural greenhouse to distribution and retail, while excluded any kind of transport from urban farm, because it was assumed that consumers buy directly from it. Waste management is the phase where production waste is handled for disposal to landfill, reused, or recycled, those analyses that include such phase considered impacts only from wastes produced in farm and disposal to landfill of infrastructure and auxiliary materials, as well as their transport. Recycling of materials, in some articles, were not accounted for the environmental impacts as cut-off procedure was often used (Anton et al., 2005; Llorach-Massana et al., 2017b; Sanyé-Mengual et al., 2015b), while post-consumption waste is totally neglected due to the lack of data.

In this review, a predominant reliance on mass-related FUs was observed in many studies as well as a prevalence of cradle-to-gate approach. However, consumption phase appeared to be neglected and few studies considered boundaries beyond crop production and distribution. Indeed, collecting data on this phase requires a survey of consumers' behavior regarding the amount of food purchased, how it is stored and the shopping trip (by car, by bicycle, by bus, etc.). In the case of urban farms, the omission of certain stages is often justified by short supply chains as consumers purchase directly from the farmer, minimizing transportation-related impacts (Martin and Molin, 2019; Martin, Poulikidou and Molin, 2019). However, transportation emissions avoided, thanks to this proximity-driven advantage might be counterbalanced by impacts from higher energy consumptions, especially in cold regions were crops need higher temperature to survive (Goldstein *et al.*, 2016). On the contrary, distance to distribution center plays an important role in soilless systems employed in rural settings where the use of refrigerated vehicles may have substantial environmental implications (Maaoui *et al.*, 2021; Martin, Weidner and Gullström, 2022). Food losses during market distribution and consumer's food refrigeration also bear environmental consequences (Blom et al., 2022; Maaoui et al., 2021; Page et al., 2012; Sanyé-Mengual et al., 2013) emphasizing the importance of considering these stages for comprehensive conclusions.

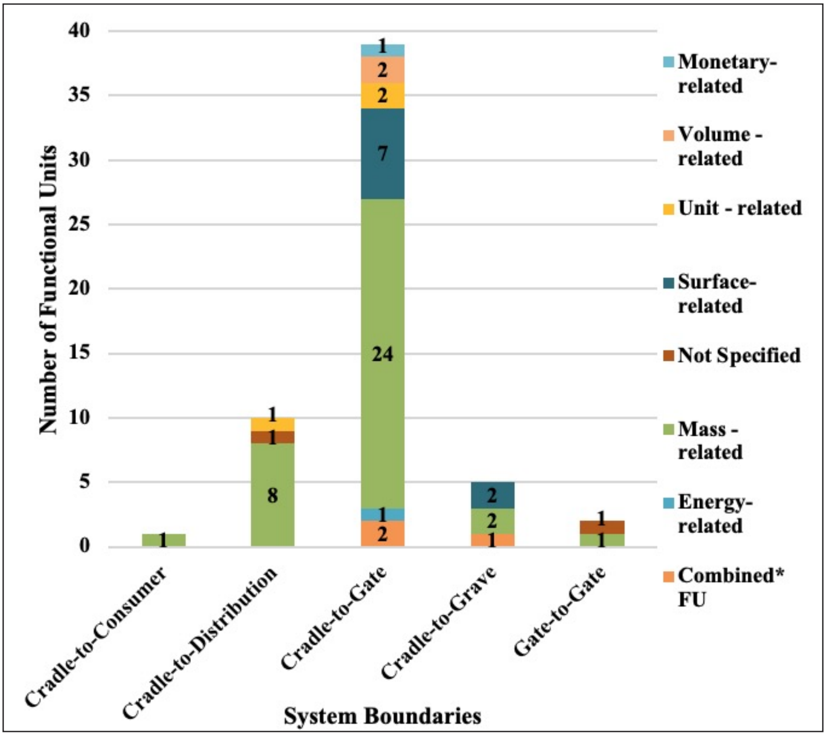

Figure 3 – Functional units and system boundaries identified among the investigated studies
*Combined FUs expressed as mass per year (e.g., kg/y) or mass per surface (e.g., kg/acre)

One of the foremost hotspots was energy consumption associated with crop production phase, in particular energy employed to heat and maintain operative the auxiliary equipment. Indeed, the production of crops within controlled environments often necessitates the use of artificial light, ventilation, cooling, and heating systems in addition to centralized controllers integrated with sensors, monitors, and pumps to deliver a well-optimized nutrient solution. Indeed, these systems can be very energy intensive, and their environmental sustainability becomes questionable depending on the share of non-renewable energy sources used to run them. For, instance, an advanced modular hydroponic container, employing a drip irrigation system, can consume 15 kWh per kg of lettuce, with an impact spanning from 0.48 to 17.8 kg CO2 eq. per kg of lettuce, depending on the energy mix used (Casey *et al.*, 2022). Energy consumption in an aeroponic system contributed to 92.5% of Global Warming Potential (100 years) during winter and 91.9% during spring, using Greece grid (Barla, Salachas and Abeliotis, 2020). Another soilless system set in Spain had an impact on Global Warming 37% higher than a conventional in-soil system due to its higher energy consumption (Martin-Gorriz *et al.*, 2021). Another prominent hotspot pertains to the synthetic substances employed for fertigation. In particular, the use of synthetic macronutrients, such as nitrogen (N), phosphorus (P), and potassium (K), also known as NPK, are essential for plant growth in soilless systems. These substance concur to substantial environmental impacts (Rothwell *et al.*, 2016; Schmidt Rivera *et al.*, 2023), particularly when employing open-loop systems (Anton *et al.*, 2005; Rufí-Salís *et al.*, 2020). Compared to an open-loop system a closed-loop allow to save daily nutrients for 40% of N, 35% of P, 41% of K, with relevant environmental benefits (Rufí-Salís *et al.*, 2020a). Whereas in open-loop systems, the drained water from the substrate, loaded with nutrient solution residues, is often collected, and subsequently discharged into the environment polluting the groundwater with synthetic substances (Bouchaaba *et al.*, 2015). The choice of materials used in the construction of soilless system infrastructure represents yet another significant hotspot. Materials such as steel, aluminum, and polyethylene, which are commonly utilized in the creation of greenhouse structures, have been identified as key contributors to environmental impacts (Ledesma, Nikolic and Pons-Valladares, 2020; Rufí-Salís *et al.*, 2020). This is particularly relevant in urban environment, were rooftop greenhouse structures may have higher environmental impact than a conventional greenhouse, because they require more material (Sanyé-Mengual *et al.*, 2015b).

4 Conclusions

A systematic review of LCA studies applied to soilless systems was conducted and a total of 46 articles were selected following the PRISMA protocols, and methodological aspects concerning FUs, system boundaries, object of the study were collected using the framework FLAVA-LCT and subsequently discussed. The results highlighted that mass-related FUs, and cradle-to-gate approaches were dominant, reflecting the attention on the production phase. Post-farm and consumption phase received less attention, possibly due to lack of data. Moreover, reviewing the selected articles allowed to shed light on the potential hotspots of soilless systems, which are concentrated in the production phase. Indeed, the contributors of these impacts are energy consumption, nutrient solution (in the form of NPK) and materials the greenhouses are made of (like steel, aluminum, and polyethylene). Without addressing these shortcomings, soilless systems can be less environmentally sustainable then conventional systems (Rothwell *et al.*, 2016). Possible solutions may involve the use of renewable energy sources (Martin-Gorriz *et al.*, 2021), reduced doses of nutrient solution (Muñoz *et al.*, 2008), alternative fertilizers and recycled materials (Corcelli *et al.*, 2019; Arcas-Pilz *et al.*, 2021).

Future research should focus on comparing the most recent and innovative soilless system against the most used ones, employing different FUs and broader system boundaries to include post-farm and post-consumption phases. In addition, further analysis should encompass all methodological choices which are made across the four cardinal steps of LCA.

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