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COMMENTARY

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Rethinking organic fertilization in soilless systems: context, circularity and the need for a common framework

Veronica Arcas-Pilz* and Francesco Orsini

Abstract

While taking big steps to increase the sustainability of soilless production systems through the integration of organic fertilization sources, the drivers and premises for their implementation do not seem to be entirely covered. There has been a scattered experimental approach to finding suitable organic sources and nutrient recovery technologies to overcome technical limitations, which seem relevant in the system's footprint. Although recognized by some, the acceptance of soilless agriculture under the organic label is still under debate. This brief commentary addresses the concept of organic fertilizers in soilless agricultural systems, highlighting the importance of common premises to move forward. These include the local context of implementation, the choice of technology, scale and organic fertilizer source, as well as the employment of tools to integrate agronomic optimization with accurate analysis of environmental and economic sustainability performances. The importance of the organic waste source is discussed, considering it pertinent to align with the underlying principles of low-input farming, avoiding the generation of non-sustainable market chains or new waste for the sake of its circularity. Finally, it is proposed to strive for an alternative certification system for low-input and circular farming systems with common goals, also based on needs and available resource flow in urban and industrial settings.

Significance of the study

1. What is already known on this subject?
   The subject of organic fertilization in soilless agriculture is being greatly explored, while the strategic pathway and the requirements for the implementation can be unclear and underrepresented.
2. What are the new findings?
   The present text does not present new data but intends to shed light on the challenges and inconsistencies of the current research direction, as well as encourage the definition of separate goals for certification in circular soilless systems.
3. What are the expected impacts on horticulture?
   The present document aims to foster critical thinking on the choice of organic sources, emphasizing scalability and contextual awareness while avoiding reliance on unsustainable sources.

Keywords: soilless agriculture, bioponics, organic fertilizer, nutrient circularity, organic certification

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CABI

Introduction: understanding strategies, technologies and drivers

Soilless agriculture (also referred to as hydroponics) has been expanding as a plausible strategy for urban and controlled environment agriculture, achieving great yields, adapting to narrow spaces and occupying urban areas for horticultural production. Hydroponics, thanks to the precise delivery of nutrients directly to plant roots and the adoption of closed-loop systems, is highly efficient in the use of nutrients and water, thereby reducing fertilizer losses. Nevertheless, even if greatly optimized, soilless agricultural systems are inevitably dependent on mineral fertilizers, subjecting operational costs to global market trends, reducing their implementation capacity in remote areas, and lowering their long-term sustainability.

The search for alternative fertilizer sources for soilless agriculture has attracted major research efforts, with a special focus on organic waste as a promising foundation. The technologies, or rather the terminologies, for nutrient recovery strategies most prominent in current literature are without a doubt bioponics with their less popular derivatives, also named upon the source waste used, such as *poultryponics* in the case of poultry processing water (Arthur *et al.*, 2025), *anthroponics* in the case of human waste such as urine (Sohn *et al.*, 2024), and the more commonly adopted *aquaponics*, using fish droppings as source of nutrients, although sometimes considered separate from the bioponics umbrella (Wongkiew *et al.*, 2021).

The concept of bioponics, as expressed by Szekely and Jijakli (2022) is the recycling of organic material through the synthesis of a nutrient-rich solution to be then fed through the irrigation of the soilless system. Organic fertilizers contain nutrients primarily in complex organic forms that require microbial mineralization before plant uptake. This mineralization process, while occurring spontaneously in natural ecosystems, is enhanced in what Szekely and Jijakli (2022) classify into four methods (Fig. 1), hereby listed from lower to higher infrastructure requirements:

The ‘tea‘ or ‘extract’ method produces organic nutrient solutions by brewing compost or manure in water to create compost or manure teas, while the aerobic degradation method uses beneficial microorganisms under oxygen-rich conditions to break down organic matter and convert ammonium into nitrate.

The anaerobic digestion method breaks down organic matter without oxygen, producing biogas (a renewable energy source) and a nutrient-rich digestate that serves as an effective organic fertilizer.

And finally, the fourth method consists of combining anaerobic digestion with microbial aerobic mineralization.

The drivers behind the change in fertilizer source can be multifaceted and not solely based on cost reduction or the remoteness of the system.

Unquestionably, one of the main claims for the use of organic fertilizers is to increase the sustainability of the production systems using local resources, reducing the need for mineral fertilizer imports, such as the case of Thailand, which, as described by Endoh *et al.* (2024), imports more than 80% of its domestic use of mineral fertilizers, or the European Union relying on the imports of 30%, 68% and 85% of N, P and K, respectively (European Comission, 2022).

While independence from external markets is important, great emphasis has been placed on an institutional level on increasing resource circularity as a key player in raising the environmental sustainability of food production. Such is the case of the food waste valorization strategies as expressed by the European Environment Agency (2020) or the role of nitrogen and phosphorus nutrient circularity, including food waste and human excreta, as strategies to limit food production emissions within planetary boundaries, as reported by the 2025 EAT-Lancet Commission (Rockström *et al.*, 2025).

Finally, we are met with the most controversial driver, which would be to score points for an organic certification of products cultivated in soilless systems (Di Gioia and Rosskopf, 2021). While this article does not intend to delve deeply into the debate on the use of organic certification in soilless agriculture, at this stage, it is essential to acknowledge the interest from the sector in further discussing the maturity of these new systems or the conceptual adequacy required to be recognized as such.

Technical and biochemical constraints and the development of current research

The use of organic fertilizers faces significant technical and biochemical constraints, which have been previously defined by Junge *et al.* (2025) as important drawbacks in the implementation and safety of the technology. Nutrient availability is often unpredictable, as organic sources release nitrogen, phosphorus and other elements slowly and irregularly, which can lead to deficiencies or imbalances in systems lacking robust microbial communities. The mineralization ratio in compost or manure tea can be low if not properly implemented, compromising nutrient availability and plant yields as well as risking phytotoxicity. These same symptoms can be experienced when applying anaerobic digestates, which typically contain high ammonium concentrations but show deficient quantities of other key nutrients, therefore being a risk for plant toxicity or nutrient insufficiency (Dsouza *et al.*, 2021; Heintze *et al.*, 2024). Organic inputs also promote microbial growth, which can be beneficial in soil but detrimental in semi-sterile hydroponic environments, as excessive microbial activity increases biological oxygen demand (BOD), depletes oxygen in the root zone and may promote anaerobic conditions harmful to plants (Szekely *et al.*, 2023). Furthermore, solid residues and biofilms from organic fertilizers can clog irrigation emitters (Lau and Mattson, 2021) and generate odours (Billones *et al.*, 2025; Mu *et al.*, 2025), potentially increasing operational costs and reducing their implementation.

Collectively, these factors undermine one of hydroponics’ central advantages, its precision. In other words, integrating organic fertilizers reintroduces the biological complexity that hydroponics was designed to avoid.

To overcome these limitations, additional treatment steps are often necessary, which inherently increase the system’s complexity, energy demand and infrastructure requirements. Aerobic mineralization, or the combination of aerobic and anaerobic processes, can improve the fertilizer quality by promoting nitrification, lowering pH, reducing organic compounds and enhancing nutrient solubility and stability, but it requires continuous oxygenation, controlled conditions and often more sophisticated reactors or sequential batch systems (Guruchandran *et al.*, 2024). Similarly, dilution,

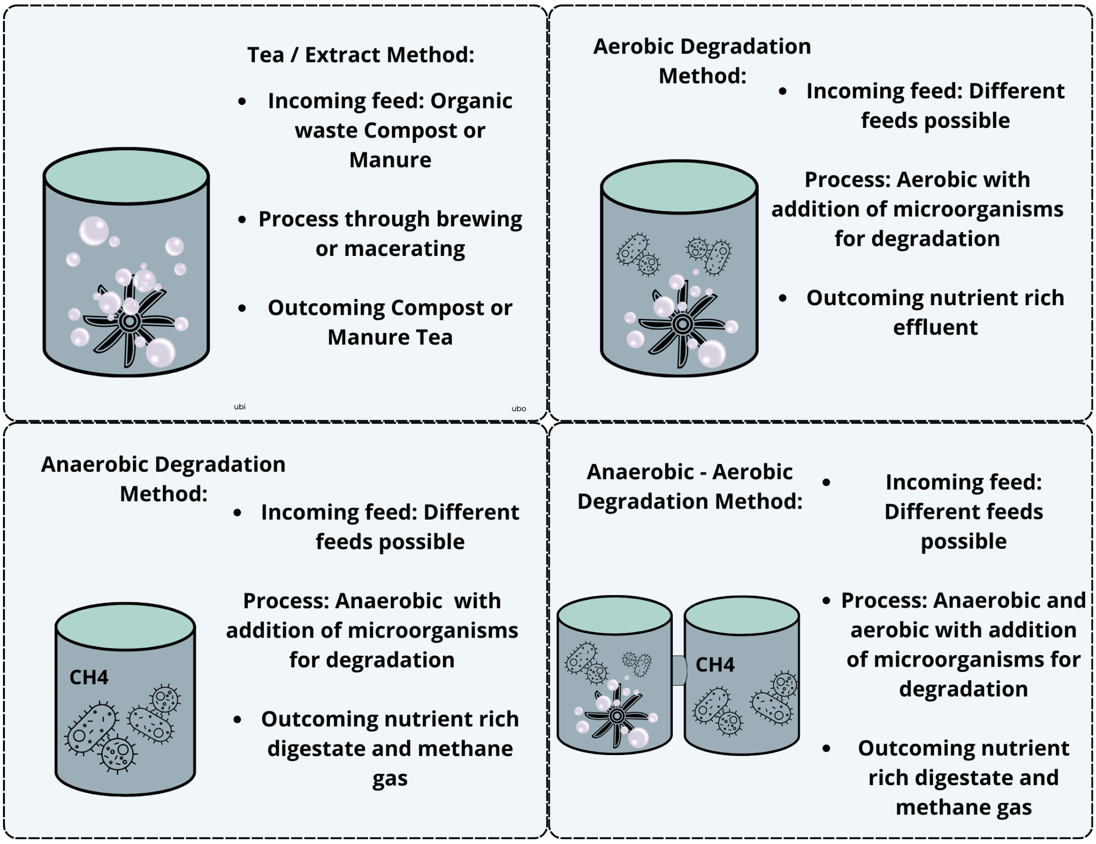

Fig. 1 Schematic overview of the four nutrient mineralization methods as expressed by Szekely and Jijakli, 2022.

nutrient balancing and careful pre-treatment of digestates are needed to prevent ammonium toxicity and ensure adequate nutrient availability. Other processes, such as chemical precipitation of struvite, membrane filtration and resin adsorption, have been widely used in wastewater as well as digestate treatment, requiring the addition of chemical reactants, infrastructure and energy (Pradel and Aissani, 2019; Arcas-Pilz *et al.*, 2023).

The negative effect of the treatment process on the overall environmental footprint of the nutrient recovery or crop production in bioponics has been reported in relevant literature. In the case of Maiza *et al.* (2025), a pilot-scale aerobic reactor was used to boost the nitrification process of ammonia from source-separated urine. The study reported that the processing energy and the aerobic reactor structure were major contributors to the process footprint, making it a less sustainable option than the baseline scenario. Similarly, the results obtained by Fan *et al.* (2025) revealed an impact increase when substituting mineral with organic fertilizer to produce cantaloupe in a soilless system. This increase was associated with a greater energy requirement as well as a slight reduction in the yield. Direct emissions occurring during pre-treatment processes can also be determining factors of the overall impact, as discussed by Desaulniers Brousseau *et al.* (2024), pointing at the importance of greenhouse gas (GHG) emissions such as N_2O during aerobic biological processes, responsible for a dramatic increase in the overall impact.

When skimming through current research on bioponics implementation in experimental settings, it is often the case in which a combination of wastes is used, in different ratios and even different mineralization stages to overcome potential nutrient imbalance (Cantero Torres and Galo Somera, 2022; Heintze *et al.*, 2024; Park and Williams, 2024). These combinations are formed from a variety of animal manure, food and industrial waste, along with the addition of amendments, rendering replicability complicated and scalability virtually impossible.

The additional technologies and the choice of feed substrate can make organic and digestate-based fertilizers safer and more effective, but they increase the technical and operational complexity compared with conventional mineral nutrient solutions, which are more predictable, easier to manage and capable of achieving higher yields without intensive processing.

The importance of finding a common framework

This premise serves to understand the current conundrum we are in.

Soilless systems using organic fertilizers are often not recognized under the organic label, do not seem especially sustainable when considering the need for additional infrastructure and operation and, in the aspect of circularity, current research may not embody the reality contemplating very unrepresentative waste mixes.

At this stage, it is only normal to ask ourselves if we are truly taking steps into the right direction. And arguably, for this progress to be meaningful, we need to become more strategic in implementing organic fertilization approaches within soilless systems.

Understanding the 'context in which we are fitting our system is crucial. A previous system analysis can help us understand key leverage points to tackle in waste production, collection, disposal and transformation, as well as the existing infrastructures available. A previous material flow analysis (MFA) of a system can take us a long way, not only ensuring the representativeness of waste in a system but also the bulk and frequency of supply, as well as potential compatibility with residence periods for mineralization or nutrient recovery processes. Examples of this approach are the cases of Arosemena *et al*. (2024) when discussing municipal solid waste, Rufí-Salís examining struvite production from wastewater on a municipal scale, or even the use of multiple resources such as source-separated urine and greywater on a building cluster level as proposed by D'ostuni *et al*. (2023).

In addition to an MFA, experimental studies recovering organic nutrients in soilless systems should not only deliver agronomic outcomes but also explore economic and environmental indicators using tools such as Life Cycle Analysis (LCA) and Life Cycle Costing (LCC) to evaluate the true sustainability of these systems. If designed with the local context in mind, LCA and LCC results can be influenced in a favourable way, especially when considering existing transformation processes and infrastructures. These premises may help benefit from economies of scale, such as in the case described by Mbaya *et al*. (2017), who modelled the environmental impact of human source-separated urine to produce struvite in dense cities, benefiting from building infrastructure and large-scale production capacity. These results are further reflected in the work developed by Maiza *et al*. (2025) where nitrogen recovery from source-separated urine, using an aerobic reactor, was analysed on a building level, with the goal of utilizing it as a nitrogen source for hydroponics, and determining the need for greater scale processing to achieve environmental sustainability.

Although not directly addressing organic nutrient implementation in hydroponics, the case study assessed by Firmansyah *et al*. (2021) applied environmental, economic and social indicators to identify the most optimal nutrient recovery strategy from waste on a small island in the Caribbean, identifying best performances in centralized processes through an anaerobic sludge bed and trickling filter systems. This approach can help define sensible waste streams and recovery technologies that can then be tested in bioponics.

As briefly described by Pradel and Aissani (2019), the combination of agronomic data with environmental assessment of the organic fertilizer production and use is crucial since its environmental sustainability can be highly sensitive to its fertilizing values as well as any other attribute that might contribute to plant health. In this case, organic fertilizers might have a lot to offer, such as the slow-releasing nature of struvite in the reduction of fertilizer loss, which can be relevant in simplified and linear systems, while maintaining or increasing crop yields (Arcas-Pilz *et al*., 2021, 2022; Thiebkhun *et al*., 2024), the content of specific compounds with biostimulant capacity (Antón-Herrero *et al*., 2021; Campana *et al*., 2025) or the increase of the plant nutritional value (Alneyadi *et al*., 2024; Alkaabi *et al*., 2025).

Striving for the organic certification might be a motivation for the use of organic fertilizers in soilless agriculture; therefore, the aim must be always to uphold the basic rules of the organic production, even if the soil and animal welfare are not directly present.

What this means is that the presence of organic soilless agriculture should directly or indirectly help promote environmental protection, biodiversity and consumer trust to be considered eligible for the organic certification. In this sense, the source of the organic fertilizer plays an important role, and to this end, it could be questionable whether incorporating organic fertilization based on manure from intensive livestock production or from distant sources would qualify for improved environmental performance.

This statement may sound counterproductive when considering the great amounts of manure produced on a global scale, being an increasingly reported issue in Europe. In fact, these amounts are reaching a critical threshold, making it more difficult to ensure European water protection goals (EEB - The European Environmental Bureau, 2025a).

Besides, it should be assessed whether opening the gates of organic certification using manure from intensive livestock production in soilless agriculture could potentially mirror previous experiences within the biofuel industry, where the incentivization of the use of manure as feed ultimately led to an increase rather than a reduction of such waste (EEB - The European Environmental Bureau, 2025b).

As proposed by the 2025 EAT-Lancet Commission (Rockström *et al*., 2025), the evolution of sustainable food production should entail the reduction of animal husbandry; therefore, the projection of these soilless systems should not be dependent on a market that should be cut back but rather focus on the sustainable recycling of our own residues, which ultimately are undergoing similar or greater processing treatments. This could also fall into the concept of circularity, efficiency and sufficiency, as described by Spiller *et al*. (2024) who suggested that applying the idea of sufficiency to livestock production greatly reduces the margin for circularity of resources within that system.

This, of course, is not always the reality in all parts of the world, where production on soil is not possible in a rural context due to heavy soil contamination, and where animal manure can serve as a local resource for simplified organic soilless systems (Mununga Katebe *et al*., 2024).

To this end, rather than insisting on defining the organic soilless systems as 'natural', we should embrace their function within the 'de-naturalized' urban and peri-urban ecosystems, leveraging existing wastewater treatment or organic waste processing facilities to reduce costs and environmental burdens, which is a goal increasingly aligned with European regulatory frameworks on waste reduction and nutrient recycling.

Steering away completely from the 'organic label' and creating an alternative terminology with a set of goals adequate to encourage circular strategies within soilless agriculture would be far more interesting. A similar concept has already been proposed by Gonnella *et al*. (2021) indicating the need to include a certification process taking into account the environmental impact as well as product quality in the sense of its nutritional value and taste. Similarly, Cirone *et al*. (2023) proposed a sustainability scoring framework to evaluate social, environmental and economic performances of farms, which also accounts for resource circularity. Accordingly, overall product sustainability could also result from spatial proximity between fertilizer production, crop cultivation and consumer, thereby enhancing local integration and circularity within the food and waste value chain.

To prevent soilless agriculture from ultimately displacing soil-based agriculture, while simultaneously capitalizing on its independence from arable land, the concept of land sparing for conservation purposes could be strategically incorporated into new certification goals, incentivizing the use of non-arable spaces. Additionally, this approach should consider both the direct and indirect benefits in resource use attributed to the organic fertilizer source, as well as the benefits of implementation in soilless agriculture, which prevent nutrient leaching into soil and water bodies. However, the concept of sufficiency of the primary product generating organic waste should be defined and incorporated to avoid overproduction and a false sense of environmental soundness through circularity.

These parameters are only a first set of premises that can help define an alternative scoring system for circular soilless agriculture, keeping in mind the importance of achieving transparency and building consumer trust based on the same principles shared under organic certification, which is highly relevant to convincing and attracting farmers' adherence.

CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

ETHICS STATEMENT

The authors confirm that the research meets any required ethical guidelines, including adherence to the legal requirements of the study country.

AUTHOR CONTRIBUTIONS

All authors contributed equally to the development of this article.

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DATA AVAILABILITY

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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