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Toward nutrient cycling from organic waste streams for soilless cultivation

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Soilless cultivation offers multiple benefits, such as higher productivity, reduced pesticide use, maximised water use efficiency, and protection from adverse environmental conditions, and will play an ever-greater role in providing food for the growing population. Whilst hydroponics denotes the use of nutrients of mineral origin, bioponics connects organic waste streams with microbial transformation and soilless cultivation, placing it at the centre of circular food production. Commercial bioponic growers need industrially produced fertilisers that are consistent in their quality and produce comparable yields to mineral fertilisers. This opinion piece examines four key issues that we think will determine whether recovered fertilisers become widely adopted by commercial soilless growers — efficacy, safety, sustainability, and economic viability — and concludes by proposing a roadmap to guide their development.

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Introduction

Six of the nine boundaries of Earth system processes that are essential for maintaining the stability and resilience of the planet have been transgressed, including land system change, freshwater use, and biogeochemical (nitrogen and phosphorus) flows [1]. The food system is among the leading causes, since agricultural activities in many regions are using too much land, water, and/or fertiliser. Global applications of nitrogen (N) for food production increased from 21 million tons in 1995 to 31 million tons in 2015, while phosphorus (P) use increased from 22 to 27 million tons over the same period [2]. Excessive use of N and P has substantial consequences, notably the eutrophication of aquatic and terrestrial ecosystems, reducing their biodiversity and ecosystem functions.

To push nutrient losses back into the safe operating space of Earth system processes, transformation towards sustainable food systems that will support a population projected to reach 10 billion by 2050 will require efficiently using N and P without releasing more reactive N and P into the biosphere. This necessitates efforts to recover nutrients in usable forms from primary production, food processing, and waste treatment. The Fertilising Products Regulation (EU) 2019/1009 sets quality standards for fertilisers made from organic by-products and waste and creates a common market for these in the European Union, thereby promoting an increased use of recycled nutrients and reducing dependence on nutrients from third countries. In light of the regulation, this opinion piece examines the potential for using recovered fertilisers in soilless cultivation and proposes a roadmap for transforming soilless farming towards circular food production.

Soilless cultivation

The productivity of soils is declining as they become increasingly degraded due to unfavourable environmental conditions (e.g. air quality, climate change) and increasing intensity of agriculture (overuse of fertilisers, pesticides and herbicides, salinization) [3]. While the global availability of arable land is declining, the area used for crops in greenhouses is increasing and covers 1.3 million ha globally [4].

Resource-efficient horticulture using soilless cultivation will play an escalating role in providing food for the growing population. Commercial soilless cultivation, including vertical farming, is gaining momentum, and its primary role can be viewed as providing high-value crops (i.e. vegetables, herbs, medicinal and aromatic plants) with high micronutrient (i.e. mineral and vitamin) content. Increasing dietary diversity is one of the strategies for alleviating hidden hunger [5].

The benefits of hydroponics include higher productivity, reduced pesticide use, and maximised water and nutrient use efficiency [6]. Soilless systems avoid the negative impacts of water run-off, soil erosion, and nutrient loading associated with field-based agriculture [7], as well as the risk of soil-bound pests and diseases and the transfer of pollutants and human pathogens from contaminated soil.

In addition to hydroponics, recently many '-ponic' terms have emerged, all denoting soilless cultivation: bioponics, aquaponics, anthroponics, digeponics, fogponics, aeroponics, and organoponics, causing some confusion about their meaning. Soilless systems can be categorised according to several dimensions (Table 1). Most classifications focus on the technological solutions for the delivery of nutrient solution to the roots (e.g. fogponics, aeroponics) [8]. However, in our opinion, the most relevant dimension is the origin of nutrients in the fertigation solution. Whilst hydroponics denotes the use of nutrients of mineral origin, bioponics serves as an umbrella term for all soilless systems that use recovered resources as opposed to mined and synthetic fertilisers [9]. Bioponic systems contain a diverse community of microorganisms that perform essential functions, such as degradation and metabolisation of organic substrates and thus continuous release of plant nutrients, disease suppression, and phytostimulation. In this way, they potentially contribute to improved productivity and yield quality more than soil-based or mineral fertiliser-based systems.

Anthroponics and digeponics denote the use of human urine and digestates, respectively, as nutrient sources. Aquaponics, a circular system combining recirculating aquaculture with hydroponics, which started as a method to solve the problems of the accumulation of excess nutrients in fish water and sludge, is also a type of bioponics. Several aspects of aquaponics have received considerable attention in recent years, such as nutrient budgeting and the importance of microorganism communities, and many of the findings can be applied to bioponics in general.

Bioponics connects organic waste streams with microbial transformation and soilless cultivation (Figure 1), placing it at the centre of circular food production. Some bioponic systems, especially in urban environments, integrate all stages of the process: from the collection of organic waste to microbial transformation and cultivation. This is mostly feasible for small, low-tech, and predominantly noncommercial systems, such as those described by Gartmann et al. [10] and Mununga Katebe et al. [11]. However, for commercial bioponics, the fertiliser based on nutrients recovered from organic waste streams needs to be produced industrially.

Recovered fertilisers

Recovered fertilisers adhere to circular economy principles by recovering nutrients from waste streams. The main sources of potentially recoverable plant nutrients are domestic wastewater (greywater, black water, urine), animal manure (fish, poultry, livestock), agricultural waste, and biowaste (food processing waste, pre- and post-consumer food waste, garden and park waste). The nutrients contained in organic waste sources need to be made available to plants. The technologies used for recovering nutrients use physical (aqueous extraction, filtration), chemical (flocculation, precipitation, distillation, ammonia stripping, pyrolysis), and biological processes (aerobic and anaerobic digestion, phytoextraction). The efficacy of different nutrient recovery processes depends on the feedstock and the specific nutrients being targeted for recovery.

For soilless cultivation, the resulting fertiliser needs to have a very low level of particles to avoid clogging of irrigation systems and deposition on roots, which can

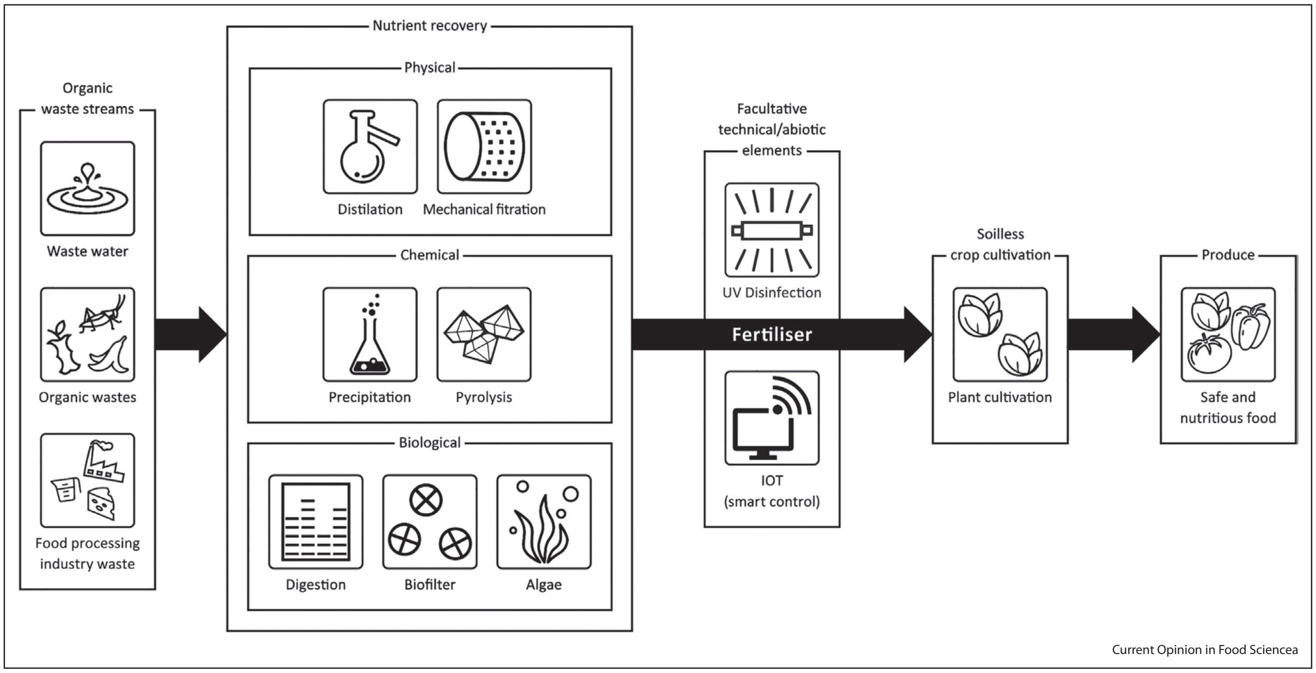
Table 1

Fundamental distinctions in soilless cultivation.

Fertiliser type	Type of soilless cultivation	Synonyms	Subgroups	Cultivation techniques
Mineral and/or synthetic fertilisers	Hydroponics	• Hydroculture		• Media Beds/Grow Beds
Biobased and/or recovered fertilisers	Bioponics	• Organic hydroponics • Organoponics	• Aquaponics • Digeponics • Anthroponics	• Deep water/floating systems • Nutrient Film Technique (NFT) • Fogponics • Aeroponics • Wicking system • Kratky system • Dutch or Bato bucket

Note that any system can be operated either as an open system (nutrient solution passes the roots only once and is discarded afterwards) or a closed system (nutrient solution is regenerated by topping up with nutrients and recirculated).

Figure 1



Bioponics connects organic waste streams with microbial transformation and soilless food production. The processes can be temporally and spatially separated, resulting in distinct industries (waste management, fertiliser production, and food production).

interfere with oxygenation. In soilless cultivation, there is no soil matrix to buffer for eventual limitations or excess of elements in the nutrient solution, so fertilisers need to have a complete nutrient profile and also not contain unwanted substances such as salt or contaminants. For growers to adopt bioponics, industries must provide specific fertilisers for specific crops and growth stages. Some companies are already producing recovered fertilisers on a large scale, such as Biota Nutri (Roelofarendsveen, NL), Van Iperen (LK Westmaas, NL), Biond (Helsingborg, SE), and Vuna GmbH (Dübendorf, CH). However, most organic fertilisers do not provide a complete and stable profile of all essential nutrients for plant growth. The problem is compounded by the fact that the definition of essential plant nutrients is not universally accepted, and there are still elements that might need to be included [12].

Unlike fertilisers, biostimulants do not directly provide nutrients to plants. Instead, they trigger specific biological mechanisms that improve plant performance, increase nutrient availability, or suppress diseases [13]. Microbial biostimulants, such as plant growth-promoting rhizobacteria and mycorrhizal fungi, can enhance nutrient use efficiency by fixing nitrogen and solubilizing phosphorus and other minerals [8]. Isolates of fungi, such as *Trichoderma* and *Penicillium*, and rhizosphere bacteria, such as *Bacillus*, *Azospirillium*, and *Pseudomonas*, display disease-suppressing and plant growth-promoting effects [14].

Microalgae and cyanobacteria are promising resources for the development of biostimulants as they contain many biologically active molecules [15]. From the perspective of the circular bioeconomy, these organisms are valued for their ability to remediate wastewater, including effluent from hydroponic farms, by removing nutrients and producing biomass that can be used for different applications, thereby avoiding secondary pollution [16]. However, while Regulation (EU) 2019/1009 permits the use of microalgae in fertilising products, those cultivated on ‘waste’ are excluded, and the use of cyanobacteria is not permitted.

Biostimulants present several challenges, including their diverse sources and compositions, which make it difficult to standardise their effect; limited understanding of the specific modes of action, which hinders the development of consistent and reliable products; the absence of clear regulatory frameworks, which complicates their commercialisation and acceptance; and the lack of methods for verifying their effect [17].

There are four main aspects that need further exploration if the use of recovered fertilisers is to become widely adopted by commercial soilless growers: efficacy, safety, sustainability, and economic viability.

Are they effective?

Fertilisers need to fulfil the physiological needs of plants, such as nutrient uptake, redistribution, and utilisation [18]. The use of organic fertilisers in soilless cultivation can be challenging, since many nutrients bound within organic substances are not accessible for direct plant uptake, necessitating microbially mediated mineralisation to release them [19]. If the nutrient solution does not match the specific needs of the plant, it leads to limitations due to missing nutrients, and the accumulation of unused nutrients in the nutrient solution.

One way to approach the coupling of nutrient recovery with plant cultivation is via the stoichiometry of the elemental composition. Both nutrient limitation and the accumulation of undesired substances in a circular process reflect the (mis)match of the elemental composition of material streams. There are 92 naturally occurring elements on Earth, of which only about 30 are widespread, and very few are important for life. The frequency, and with that the availability, of elements in the Earth's crust does not match their frequency in living beings. Plants, for example, generally contain lower fractions of N and P than animals. This can also be illustrated by aquaponic systems. The aquaculture part of the system provides most plant nutrients in lower concentrations compared with standard hydroponic solutions. Moreover, the ratios between these elements are highly variable [20]. This mismatch causes nutrient limitations, which require targeted supplementation of minerals to enable better utilisation of the entire spectrum of elements, while unassimilated nutrients accumulate in the recirculating water [21]. However, organic matter in bioponics is continuously being mineralised by a diverse microorganism community and plant nutrients are thus released over time. Therefore, whilst the dissolved nutrient levels might be lower than in hydroponics, they are always available, albeit in small quantities.

Whilst mixing an optimal solution of mineral fertilisers is feasible and many tested recipes are freely available, the use of recovered fertilisers is more complicated. Owing to the inherent mismatch between the needs of the plant and the nutrients provided in the fertiliser, supplementation with specific nutrients will be needed to achieve comparable yields. Experiments with bioponics confirm this. Using water extracts of manure [22], manure digestate [11], liquid biogas digestate [18], biogas digestate concentrate and biochar [10], or nitrified urine [23], without supplementation of mineral nutrients, resulted in lower yields compared with hydroponics. On the other hand, trials that added nutrients to achieve approximately equal levels to reference mineral solutions showed similar or even better yields [24,25].

One way to obtain a more balanced bioponic fertiliser is to treat the sources separately to obtain stock solutions, which are then combined. For example, [26] obtained N-, P-, and K-rich stock solutions from blood meal, bone meal, and potato peel, respectively. However, their composite nutrient solution still performed worse than the standard hydroponic solution.

Organic material and the products of its degradation may have phytotoxic effects [27]. While the microorganism community releases nutrients over time and can aid in the suppression of diseases, it may also have a profile that is not beneficial for plants. The microbial community may also grow too abundant and compete with plants for nutrients and oxygen, causing O_2 depletion in the root zone, which needs to be counteracted with aeration. At the same time, release of NH_4 may necessitate the inclusion of nitrifiers.

A trial using a recovered fertiliser with and without a microbial inoculant containing a proprietary blend of beneficial plant growth-promoting rhizobacteria, with a conventional hydroponic fertiliser as a control, revealed that plant growth with the organic fertiliser and inoculant combination was superior to that in the treatment without the inoculant, and equal to that in the control [28]. The efficacy of microalgal [29] and cyanobacterial [30] extracts as biostimulants has also been demonstrated.

Are they safe?

Vegetables accumulate nitrate depending on fertilisation regime, salinity, light intensity, temperature and season, and species/variety. Some studies showed lower levels of nitrate in lettuce leaves in bioponics than in hydroponics [10,25], while others showed higher levels [24,31]. There are established strategies to reduce nitrate in leafy greens, some of which apply inherently to bioponic nutrient solutions, as shown by Gartmann et al. [10].

Heavy metals are absorbed by plants as a function of their concentration in the environment and can surpass the permissible levels defined by Regulation (EU) 2023/915 on contaminants in food. Depending on the digestion conditions, the degree of elimination of heavy metals varies highly. Heat treatment and the subsequent use of solid/liquid separation, as applied to the biogas effluent concentrate used by Gartmann et al. [10], can significantly decrease heavy metal concentrations in the liquid. This explains why lettuce cultivated in bioponics using concentrated liquid digestate had levels of Cd and Pb below the detection limit, and Cu and Al levels were no higher than in plants cultivated in soil and hydroponics [10]. However, the potential risks of heavy metals, in terms of food safety, should be investigated further.

Both unprocessed and processed waste from agriculture and wastewater treatment can be a source of organic micropollutants. Tertiary wastewater treatment removed very different fractions of micropollutants, revealing the potential risks of using reclaimed water in hydroponics [32]. While mesophilic and thermophilic anaerobic digestion degraded organic micropollutants from sewage sludge to a certain extent, only thermophilic conditions decreased estrogenicity [33]. Micropollutants, such as some antibiotics, antipsychotics, and antidepressants, which are typically persistent during aerobic wastewater treatment, are better removed by anaerobic processing [34].

Steroids can only be degraded by microorganisms [35]. Because of low aqueous solubility and complicated structures, degradation under anaerobic conditions is much slower and requires combined aerobic/anoxic conditions [36]. The review of plant uptake studies of personal care products (PCPs) using a hazard quotient (HQ) approach revealed environmental risk for some PCPs; however, no risk for consumers [37]. Few microbial studies have been conducted to determine food safety in bioponics. High temperatures during anaerobic digestion reduce pathogens and parasites [38], while ultrafiltration further reduces the bacterial load [39]. However, this also reduces microbial diversity, which plays an important role in bioponics. The use of untreated wastewater as foliar application poses potential health risks because bacteria may be resistant to common antibiotics used in medicine and animal husbandry [40]. To minimise the risks of possible contamination with pathogens, cultivation practices need to ensure that the nutrient solution does not come into contact with the edible part of the plants. This is easier to achieve in soilless systems because the crop is not fertigated from above.

Are they sustainable?

While it can be argued that the use of recovered fertilisers decreases the depletion of phosphate rock and diminishes the use of energy-intensive ammonia synthesis, the processes that convert organic waste into easy-to-transport marketable fertilising products inevitably have an environmental impact [41]. Quantification of these impacts can reach contrasting conclusions, depending on the modelling choices and assumptions made.

The logic of zero-burden assumptions needs to be questioned in the shift towards a circular economy, where waste is increasingly considered and utilised as a resource with an economic value [42].

The estimation of impacts of sludge-based P fertiliser production using a resource perspective showed that producing 1 kg of P from sludge has higher impacts than producing 1 kg of P from phosphate rock, due to the limited P yields, the energy consumed, and the chemicals used in the recovery processes [43].

Waste management and nutrient recycling are examples of multi-functional systems, providing both the function of waste treatment and the function of fertiliser production. The use of recovered fertilisers is often credited by the substitution method, which subtracts the environmental burdens associated with avoided production of mineral fertiliser. Substitution can be conducted either at product level or at nutrient level, and the choice between these methods can significantly impact the assessment of environmental benefits and potential trade-offs associated with recovered fertiliser use. The lack of a standardised approach to quantifying and reporting the environmental impacts of recovered fertilisers therefore makes it difficult to effectively convey information to end users and policymakers and creates the potential for greenwashing [44].

Is there a market?

Although the theoretical potential for nutrient recycling has been extensively explored, mineral fertilisers still dominate the market. Including recovered fertilisers within the new Fertilising Products Regulation offers opportunities for a new market to develop; indeed, the EU target is to replace up to 30% of mineral fertilisers with biobased ones.

However, resource circulation happens between and is supported by diverse stakeholders, including farmers, waste management companies, consumers, policymakers, and regulators. Understanding the ecosystem of actors that will enable mainstreaming of nutrient recycling is therefore crucial [45]. Studies of the willingness of farmers to adopt recovered fertilisers reveal that this emerging industry needs to address several technical challenges associated with their production [46], as well as challenges related to product acceptance in the context of a well-established fertiliser industry [47]. Fertiliser producers point out issues associated with the quantities and consistency of recovered nutrients, while farmers are sceptical of the advantages of using recovered fertilisers in relation to their cost and are concerned about potentially undesirable outcomes associated with their use [48].

To date, research on end-user perspectives of recovered fertilisers has focused on their use in soil cultivation [49], and information from the perspective of soilless growers is scarce and anecdotal. The adopters of soilless cultivation can be roughly categorised into four main groups, with some overlap (Table 2). They are active in two different realms, one strictly commercial, the other at the intersection of social and commercial. Owners of backyard and small-scale systems mostly implement low-tech integrated systems with self-production of recovered fertiliser (e.g. compost tea) and may be willing to substitute this with industrially made biobased products.

Since commercial growers operate at very low margins, there is no scope for trial and error. They also need a stable source of nutrients, and they have sophisticated fertigation systems in place, which would need to be adapted. Their potential reluctance to switch to recovered fertilisers could be overcome if these are cheaper. However, the fertiliser market has very low incentives for phosphorus recovery products, since it is currently cheaper to make fertiliser using phosphate rock rather than struvite, and the sales price of P recovered products relative to P mineral fertilisers is too low to justify recovery strategies on economic arguments alone [50]. This is also the case for other recovered fertilisers, except for biogas digestate. Because of the small customer base, most bioponic fertilisers therefore cannot currently compete with the prices of mineral fertilisers, and policy incentives will be needed to stimulate increased circularity of nutrients, for example, by penalising the use of mineral fertilisers and/or rewarding the use of the recovered fertilisers.

Table 2

Typology of socioeconomic profiles of adopters of soilless cultivation.

	Greenhouse horticulture	Vertical farming	Small-scale systems	Backyard systems
Scale	Hectares	Variable m^2	50–1000 m^2	> 5 m^2
Location	Rural, peri-urban	Urban, peri-urban	Urban, peri-urban, rural	
Business model	Commercial		Social, educational, commercial	Self-consumption + small income generation
Technological level	High		Medium to high	Low
Most common actors	Professional growers	Career changers: managers, engineers. Lack of technical knowledge can be compensated for by hiring professionals.		Non-professional growers, lacking technical knowledge
Potential for integration of waste recovery	Low		Medium	High

Conclusions

More efficient use of nutrients alone will not be sufficient for the food system to operate in or near the safe operating space of the planetary boundaries. Multiple measures must be implemented simultaneously, including dietary change, food waste reduction, and improved water management. Nevertheless, as more food is produced in greenhouses and vertical farms, transforming soilless cultivation towards the use of recovered fertilisers will be a step in the right direction. This transformation is becoming increasingly relevant considering the recent geopolitical instability that has disrupted mineral fertiliser supply chains and caused price volatility.

Waste valorisation industries are emerging as a key component of the circular bioeconomy. While there are synergies between the recovered fertiliser industry and the bioenergy sector through the valorisation of anaerobic digestate, there is the potential for competition for resources with other sectors, such as animal feed, biomaterials, and pharmaceuticals. Balancing the demands for biomass of different industries will require cooperation between several policy domains and a collective effort to mitigate the impact of trade-offs across different policy goals.

In addition to policy support, developing the confidence needed by soilless growers to transition to recovered fertilisers will require a targeted approach, from research and development to market implementation. Research and development will need to focus on mapping and quantifying different waste streams, researching the relationship between feedstock and product quality, developing more cost-effective nutrient recovery technologies, and piloting biobased fertilisers in real-world conditions. Product development will need to focus on developing formulations specific to different crops and life stages, conducting rigorous testing to ensure that they meet safety and quality standards, and enhancing the stability and shelf life of the fertilisers to ensure consistent performance. Market development should focus on developing business models that emphasise sustainability and circular economy principles, conducting market research to understand the demand and potential customer base for recovered fertilisers, and establishing efficient distribution channels to reach hydroponic growers and other end-users. Scaling up will require the expansion of production facilities based on pilot project results and market demand, technology transfer to other regions and countries, and using feedback from growers to improve formulations. Finally, education and outreach should involve developing training programs for growers on the benefits and use of recovered fertilisers and providing technical support to ensure successful adoption and use of the products. By following this roadmap, the development of recovered fertilisers for soilless cultivation can be systematically approached, ensuring sustainability, efficiency, and market readiness.

Data Availability

No data were used for the research described in the article.

Declaration of Competing Interest

The authors declare that they have no financial and personal relationships with other people or organisations that could inappropriately influence or bias their work. We have no competing interests to declare.

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