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Review

A systematic review of food-waste based hydroponic fertilisers

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HIGHLIGHTS

- There exists no significantly effective methodology for the consistent conversion of food-waste into an effective hydroponic nutrient solution.
- The primary obstacle to developing effective food-waste based hydroponic fertilisers is nutrient density relative to salinity.
- Utilising food-waste based nutrients challenges existing sterile cultures in hydroponic systems.
- This review suggests a framework which seeks to amend discrepancies in reporting standards.

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ABSTRACT

CONTEXT: This review article seeks to evaluate existing research in hydroponic systems which utilise a fertiliser solution derived from food-waste, also known as "Food-waste based hydroponic fertilisers" (FWBHF). FWBHF research is rooted in addressing increasing concerns surrounding food security, addressing both non-productive waste streams and sustainable production of hydroponic fertilisers. In 2018, the world was predicted to have wasted 931 million tonnes of food, 17 % of the total food produced throughout the year (*FAO, 2021*). Meanwhile, existing hydroponic systems rely on synthetic fertilisers which are constituted from unsustainable processes, such as Haber-Bosch systems or mining for phosphate rocks. These practices contribute heavily to greenhouse gas emissions or rely on destructive exploitation of finite reserves, which researchers believe will increase in price as accessible reserves are exhausted (Liu et al., 2020*;* Cordell et al., 2011). With increasing population in urban areas, the demand of produce imported from regional areas grows alongside the density of waste generation. Thus, exploring methods to re-utilise urban food-waste in urban horticultural systems may help in improving food security, reducing waste, and providing a local source of fresh produce for consumers.

OBJECTIVES: The objectives of this review article are to : i) Utilise PRISMA protocol to collect and synthesize existing literature related to food-waste based hydroponic systems, ii) Identify major challenges found across literature which inhibit yield outcomes in food-waste based hydroponic systems, iii) Explore potential improvements using conventional or non-conventional methods, including chemical, physical, and biological modifications to existing systems, iv) Suggest a standardized reporting framework for future research in this area.

METHODS: Using the PRISMA protocol, 6840 papers were identified with key words: "Food-waste AND hydroponic AND fertiliser," "Organic AND hydroponic AND fertiliser," and "Organic AND Hydroponics." 308 papers were selected based on the relevance of their title and abstract. After considering quality, overlaps, and relevance, 37 papers were chosen to be part of this systematic review. Literature was chosen based on its contents utilising any form of processing to prepare waste generated from the food-waste industry for use in a hydroponic system. These papers utilised waste generated at i) Farm, ii) Industry, and iii) Consumer, levels as well as a range of novel methods such as fermentation, steaming, or composting. This review studies how both feedstock composition and processing methodologies play a role in determining the efficacy of a food-waste based hydroponic fertiliser.

RESULTS AND DISCUSSION: It was found that while feedstock plays a larger role in the final nutritional composition, categorisation by methodology offers greater clarity for future research. This is attributed to "methodology" being the primary factor researchers can influence, with feedstock being based heavily on regional, industrial factors.. Overall, no clear trends or processing methods were identified as being particularly effective, with the strongest relationship between a FWBHF and positive yield outcomes being its similarity to the

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corresponding synthetic control solution. Synthesis of existing literature identifies two key avenues for future research: i) nutrient/salinity imbalancesand ii) microbial activity. Nutrient deficiency and excess salinity are identified as the main limiting factors in FWBHF research and are closely related. N deficiency was the most recurring nutrient deficiency, although deficiencies in P were also common. Excessive salinity limits plant available macro-nutrients and was more frequent in research which utilised food-waste generated at "consumer" levels. Cultivating microbial agents may potentially improve overall plant yield by improving mineralisation of nutrients, assisting rhizosphere efficiency, or by antagonising pathogenic species. Finally this review suggests a standardized reporting system. The infancy of this research leads to irregular reporting standards. The suggested reporting procedure seeks to amend discrepancies by clearly establishing a list of 21 factors which have been reported across the available literature and attributes a priority ranking to the relevance of the paper based on its field of study.

SIGNIFICANCE: This review article seeks to develop a synthesis of existing research for a clearer direction of development for food-waste based hydroponic research. This research is important as it aims to accomplish three goals in urban environments: i) Provide economically beneficial, local, and sustainable use for food-waste, ii) Improve their own food security by increasing local food production, and iii) Develop sustainable urban horticulture practices.

1. Introduction

In the context of this review, food-waste is defined as the organic by-products discarded by food- producers, processors, or consumers at any stage between harvest and consumption for reasons of quality, quantity, or redundancy.

The 2021 United Nations Environment Programme Food Waste index reported that the world generated931 million tonnes of food-waste in 2018 – accounting for 17 % of the total 5.3 billion tonnes of food produced throughout the year. The impacts of these losses are best appreciated when considering the resource-intensive processes that are involved in food production: land-clearing, soil erosion, fertiliser inputs, greenhouse gas emissions, as well as energy and fuel used to add-value, store, and transport products. As the world population continues to grow, and food security is challenged by increasingly unpredictable climate patterns, it is important that methods to re-incorporate food-waste into food-production systems are explored – with the aim of limiting nutrient leakage.

The concept of developing productive uses of food-waste is particularly important in cities due to their dependence on international and regional food imports. Nations such as Australia will benefit most from research into the re-utilisation of food-waste. This is due to a high percentage (86 %) of the population living in urban areas (Australian Bureau of Statistics, 2022), comprehensively documented food-waste management streams, and significant investment into urban horticulture infrastructures. In addition, it is inevitable that urban environments are net importers of food, however highly developed nations such as Australia, tend to have a comparative surplus of food waste compared to the world average – with the average Australian household generating 102 kg of household waste per capita compared to the world average of 74 kg/capita (United Nations Environment Programme, 2021). Existing waste-streams in Australia include household waste (34 %), primary production (31 %), manufacturing (24 %), and consumer facing services (10 %). Overall, the total amount of food-waste per capita in Australia is estimated to be 298 kg (FIAL, 2021). The extent of food-waste processing in Australia primarily targets primary and secondary industry waste-streams. Generally, food-waste is either recycled, recovered for biofuel, or disposed. Recycling involves the reutilization of waste in a functional manner, with examples ranging from using eggshell waste in pharmaceutical products, coffee grounds incorporated into cosmetic products, or simply the recovery of nutrients within food-waste to produce more food in the future. A 2014 census by *Food Innovation Australia* (FIAL,2021) found that only 14 % of waste generated by Australian households is composted in-house or commercially. Comparatively, 72 % of waste generated by primary and secondary industries are recycled. Energy recovery relies on stored nutrients in food-waste to feed methanogenetic microbes which produce biogases that can be used as a source of combustible energy. In 2021, only 28 t of industrial waste was utilised as a source of energy. Finally, disposal is the least desirable outcome, as there is no additional benefit extracted from the food-waste before it is discarded. In Australia, 69 % of consumer waste ends up in landfill, which comprises up to 95 % of the total food-waste in landfill. The remaining 5 % is produced by secondary industries which, despite generating more than double the amount of waste compared to consumers, only send 1.5 % of generated waste to landfill. This is likely attributed to value-adding or recycling processes which can be applied to the large amount of homogenous waste products produced by primary industries such as abattoirs, food refineries, or other intermediate processes products undergo prior to retail or wholesale availability. Primary industries in Australia do not utilise landfills (FIAL, 2021)

This paper explores the potential for recycling food-waste into liquid fertilisers for hydroponic systems as a response to increased import dependence and growing food-waste. Overdependence on regional and international food imports can threaten overall food security (Luo and Tanaka, 2021). Again, in Australia this is a growing concern, with Sydney city reportedly importing 90 % of its vegetables and 98 % of its fruit from regional and international sources (SFF, 2016). Developing sustainable urban horticultural systems are a budding solution to alleviating the pressure on regional and international importers to provide a secure source of affordable produce to urban areas (Taghizadeh, 2021). While there has been extensive research (Ouro-Salim and Guarnieri, 2021) performed into transforming food-waste into effective on-field fertilisers, these solutions often rely upon microbial elements in soil to convert inaccessible organic material into plant available forms. In hydroponics, the absence of soil removes a critical medium required for the regulation of appropriate nutrients. This initial obstacle is compounded by the non-homogenous inputs of "food-waste", which often include fatty, heavily salted, and non-sterile components.

The benefits of adopting protected hydroponic systems include improved space efficiency, smoothing supply shocks, reducing transport logistics, and extending food security into urban and peri-urban areas. Hydroponic systems can combat the loss of arable land as a result of soil degradation, urbanization, and increasing climate variability (Wallace et al., 2015). This is achieved through offering optimal growing conditions throughout the year by emulating ideal soil and atmospheric conditions, bypassing traditional cropping density limitations. In such conditions, systems are capable of doubling cauliflower yields, improving the yield of peas by 7 times, and tomatoes by 18 times when compared to traditional soil-based systems per acre (Sardare, 2013).

A limiting factor in adoption is the significant resource investment required to achieve such levels of yield efficiency. Generally, a large amount of capital is required to purchase land, infrastructure, lighting, and machinery. Ongoing upkeep costs such as fertilisers, water, substrates, pH adjusters, pots, and electricity further limit the type of crops hydroponic systems can profitably cultivate. As such, the practicality of these systems generally exclude arboreal and broad-acre crop species.

Instead, seasonal, high-value horticultural crops are ideal, including leafy greens, berries, fruits, and other vegetables. The limitation of crop species, however, may not significantly impact the urban or semi-urban viability of such hydroponic systems. Annual availability of locally sourced produce provides a competitive edge for local producers, especially when competing against out-of-season imported products (Armanda et al., 2019). In addition, providing alternatives to regional or international imports bolsters food security in both short- and long-term scenarios. Disruptions in horticultural food chains tend to have a more profound effect on short-term availability compared to broadacre cereals or other long-life products. This is due to the fragility and short-shelf life of many horticultural products, evidenced by relatively more variable pricing of fresh produce compared to grains. In 2019, CSIRO reported that between 18 and 22 % of all horticultural goods in Australia were wasted during production, processing, and transportation stages (Juliano et al., 2019). Although no empirical evidence exists to quantify losses during transportation, causes of damage at this stage include disruptions in the cold chain, disease, and mechanical damage (Parfitt et al., 2010). Food-waste as a result of transportation is also reduced in urban and peri-urban cropping facilities. By reducing transportation distance, and thus time spent in transport, a less extensive logistical network of refrigeration and atmospheric control is required to preserve food quality. This reduces overall risk factors that contribute towards food-waste, as well as contribute towards reducing the carbon footprint of food transportation, which accounts for 27 % of global freight emissions (Li et al., 2020).

As a result of increasing commercial adoption, research efforts in hydroponics have increased, including improvements in energy and water efficiency. In 2019, a life cycle analysis found that hydroponic systems have greater energy and input requirements when compared to conventional cropping systems (Martin and Orsini, 2022). While there is constant research into optimising production methods, management, and energy efficiency, the crux of hydroponics relies on its nutrient fertiliser designed to emulate the mineral composition of fertile soils. Due to their synthetic origins, these solutions have constituent inputs sourced from unsustainable processes, such as extracting nitrates from the atmosphere with energy intensive Haber-Bosch systems or mining for phosphate rocks. These practices contribute heavily to greenhouse gas emissions and sometimes rely on the destructive exploitation of finite resources such as phosphates, which researchers believe will increase in price as accessible reserves are exhausted (Liu et al., 2020; Cordell and White, 2011).

Current understanding of food-waste based hydroponic fertilisers (FWBHF) is largely limited. The infancy of the research area shows gaps in optimal methodology, mechanisms of organic matter breakdown, plant physiological responses to FWBHF's, optimal hydroponic system types, and so forth. This largely understudied field requires insights from a range of disciplines, including biochemistry, microbiology, plant physiology, and biochemistry. By reutilising food-waste into hydroponic solutions, three goals can be achieved, i) cities have an economically beneficial, local, and sustainable use for food-waste, ii) urban centres can improve their own food security by increasing local food production, and iii) Hydroponic systems can begin to develop in sustainable ways with potential long-term viability.

The objectives of this paper are to (i) Summarise the research performed on this topic by stage in the production chain; (ii) identify trends in successful trials and (iii) consolidate common limitations and proposed solutions.

2. Methodology

2.1. PRISMA protocol

This literature review was written utilising the Preferred Reporting Items for Systematic Review and Meta-analysis protocols (PRISMA) (Page et al., 2021). The search criteria included papers published from between 1980 and 2022 across Web of Science, ProQuest, and Google Scholar. Only peer reviewed papers were considered in this paper. The relevance of reports was considered based on two main points. First, articles which involved the creation of hydroponic fertilisers utilising organic material. Second, the origin of the materials used to develop these fertilisers.

PRISMA protocol is designed to standardize systematic reviews across a wide range of disciplines, with transparency and consistency as primary consideration for reviews written utilising the method. It includes the use of definitive screening processes which consistently identify and select relevant literature for use in a review. While it improves academic rigor, and limits bias the limitations of the method include limited temporal flexibility – meaning newer literature may be excluded after the initial Boolean searches have been performed.

2.2. Identification and selection

Across three databases, three boolean searches were carried out. At this stage, the filters used only excluded papers published before 1980, although the earliest papers relevant to this review was from 2001. The key words included: "Food-waste AND hydroponic AND fertiliser," "Organic AND hydroponic AND fertiliser," and "Organic AND Hydroponics." All papers were screened for both Web of Science and ProQuest, however only the first 300 results were considered in Google Scholar. This yielded a total of 6840 results. From these, 308 were selected based on the relevance of their title and abstract. 93 were removed due to overlaps, and a new set of inclusionary criteria was then implemented, which required papers to be peer reviewed, have a full English version, and directly related to the research objective. Finally, 37 papers were selected to be used. These papers were then categorised as: Farm, Industry, or Consumer, based on the stage of the food chain they were produced at. It is evident that this area of research has only recently gained substantial interest, as 32 out of the selected 37 papers were written after 2018, highlighting the potential for a literature review on this subject.

3. Results and discussion

The fledgling state of the food-waste based hydroponic fertiliser (FWBHF) research is highlighted by approaches from a range of disciplines, including horticulture, engineering, waste management, and microbiology. As a result, research of FWBHF's can be described as a collection of loosely related novel studies which build upon existing knowledge spanning across many fields of study. The over-arching findings of this literature review have identified 29 out of 37 papers performing growth trials comparing the efficacy of FWBHF's against synthetic controls. From the results provided, treatments with unique feedstock or methods were identified, and the most effective treatments were selected based on yield outcomes. To standardize results, yield outcomes were selected in the order of priority : i*) Fresh shoot/fruit weight, ii) Dry shoot/fruit weight, iii) Stem height*, and *iv) Leaf count.* Treatments were then categorised as follows:

To quantify and compare, this review determines solution efficacy in two ways. The first is the direct comparison of nutrient availability within a solution, and the second is found in the reported performance against a control solution. In this review, "control" solutions are generally the synthetic, conventional nutrient solution that the respective researchers have used as a comparison. It should be taken into consideration that there are a variety of conventional solutions that vary in essential nutrient content but are generally designed to optimise growth in commercial settings. There is an underlying assumption that these commercial solutions provide an industry accepted standard of performance which are valid as a general indicator of treatment efficacy, with the understanding that they cannot strictly be used to compared between studies.

It should be noted that irregular reporting limits statistical analysis.

Most notably, only 11 papers provide standard deviation, hindering attempts to determine whether a solution is statistically different from a control solution. Future research should include standard deviation, error, and other relevant statistical values, which is discussed further in *4.1 future recommendations and standardized reporting*.

Fig. 1 shows that of 29 papers, six unique treatments were identified from six papers as MY. Proportionally, consumer-based feedstock performs best, however this may not be representative of feedstock superiority – the papers included under "consumer" wastes include a combination of animal manure and kitchen waste (Loera-Muro et al., 2021), biogas (Bergstrand et al., 2020), and a variety of novel processing methods including vermiculture (Churilova and Midmore, 2019), powdering (Kawamura-Aoyama et al., 2014), and boiling (Yusuf et al., 2021). The spread of feedstock and methodology limits the accuracy of a formal meta-analysis. Instead, the most powerful correlation between a treatment and success was identified as the similarity of NPK between a FWBHF and its corresponding control solution. The impacts from specific feedstocks or methodologies were limited when considered as individual variable. It may be more important for a processing method to be selected to accommodate for the available feedstock.

3.1. Feedstock versus methods

After reading the available literature it was found that there were opportunities to categorise these papers in two distinct ways – by feedstock or by methodology. At first glance, either option provided a logical foundation for understanding existing trends in research – however closer examination identified weaknesses which may have compromised the rigidity of this review. For example, both terms are broad – requiring additional sub-categorisation into groups such as : i*) Farm waste, ii) Industrial waste, or iii) Consumer waste* for feedstock, and *i) Anaerobic fermentation, ii) Aerobic fermentation, iii) Novel methods of fermentation, and iv) non-fermentation processes* for methodology. Additionally, both feedstocks and methods found that even within the same categories, there was great variation in inputs and processing techniques across literature.

It is difficult to identify and synthesize common practices across literature when confounding factors, such as methods and feedstock have limited replications. Within similar sub-categories, there is still variation, expressed by Table 1. which looks at three papers which have been categorised as "anaerobically fermented vegetative biogas digestate."

From Table 2, despite having the same "biogas digestate" input, there are differences in the compositions which greatly impact the final product. Differences in feedstock can be observed with the inclusion of nitrate rich livestock manures, or unspecified "plant-based food-waste". Additional differences include the species used in growth trials to the presence of microbial inoculation. This can confound comparisons between solutions, as different systems produce different effects on a given solution. It should also be noted that there is variation in control treatments across studies, this creates a moving baseline for yield which is a common metric used to determine the viability of a given solution. Ultimately, this provides insight into how categorisation by feedstock may be sub-optimal for identifying trends.

Outside of feedstocks sourced from aquaponics, no two papers were alike across all the reviewed literature. The high level of variation in method and inputs is a testament to the infancy of this research area. The absence of identical feedstock replication at consumer level contributes to the difficulty of performing a comparative analysis of variables which impact measured outcomes. Instead of categorising papers based on feedstock, it was determined that categorisation by methodology would be a more effective way to identify overall trends across studies. By isolating the processes utilised there are three benefits. First, it is hoped that the characteristics of each method begin to reveal themselves across studies while being minimally impacted by inputs, system types, or crop species. Second, it refocuses the review away from grading and comparing potential feedstock and onto the processes that may be applied to develop fertilisers. Finally, it aims to recommend factors relevant to report when conducting research – a standardized structure when reporting hydroponics research.

In this review, the first part of the discussion will describe the broad trends found in feedstock and methodology. The second section will explore common obstacles faced across research, correlating factors which may have contributed to these problems, and solutions that have been developed in response. The third and final section of this review will seek to identify the role of microbial activity and ascertain its impact in the efficacy of an organic hydroponic solution.

Table 1
Definitions for quantifying treatment efficacy across literature in this review.

Outcome	Definition
Less yield (LY)	FWBHF yielded less than the control
Equal yield (EY)	The FWBHF yielded equal to was within 1 standard deviation (if given) of the control
Substituted yield (SY)	FWBHF was able to substitute a portion of a synthetic solution to produce a yield equal or greater than the control
More yield (MY)	The FWBHF was able to surpass the yield of the control

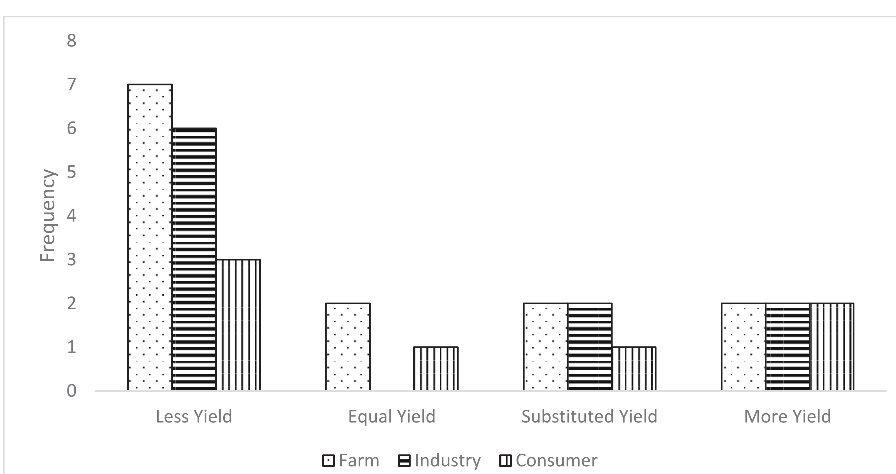

Fig. 1. The distribution of treatment efficacy across papers, categorised by feedstock origin.

Table 2
A comparison between three research papers that are categorised as "vegetative biogas digestate."

	Lind et al. (2021)	Ronga et al. (2019)	Ntinas et al. (2021)
Feedstock composition	Crop residue (85.5 %), plant-based food-waste (12.5 %), and iron chloride (2 %)	Maize silage (43 %), triticale silage (22 %), Cow slurry (27 %) and grape stalks (8 %)	"Co-digested Livestock manure and other agricultural residues"
Growth trial species	Bok Choy (*Brassica rapa* subsp. *chinensis)*	Baby Lettuce (*Lactuica Sativa*)	Baby Lettuce (*Lactuica Sativa*)
System type	Nutrient Film Technique (NFT)	Drip irrigation	Floating system
Grow period	21 days	21 days	31 days
Control	Kristalon Indigo + Calcinit inorganic commercial solution. (NPK ~19–4-20)	Hydrofood macro and micronutrient inorganic commercial solution (NPK 17–16-11), and 20 mL acidifying agent	Hoaglands solution* (pH 6.5)
Dosage method	6 L added 1–3 times a week, 2 L added 3 times a week, and 20 mL added when pH < 5.8	Diluted to 6.25 % strength. 20 L replaced each week for the first 2 weeks. Last week of crop cycle is tap water only.	Diluted with water by 5 %, 10 %, and 20 % strength with and without pH adjusted trials
Substrate used	Pumice	Perlite and solid fraction of biogas waste	Polystyrene plugs
Production method	Filtered (0.8 mm), diluted, and nitrified	Filtered (200 μm)	Filtered (1 mm) and frozen
Microbial inoculation	Yes	No	No
NPK composition (mg/L)	182–41-250	34–0** – 95	330–154 - 470

* Unspecified Hoaglands solution may refer to one of several revisions of the original recipe.
** P2O5 absent in liquid extract, but available in solid byproduct at rate of 60 mg/L.

3.2. Discussion of feedstock

While the synthesis of literature is distinguished through methodology, understanding the properties and potential of inputs is relevant to a comprehensive perspective of organic hydroponic solutions. The feedstock of a fertiliser is essential - nutrients that do not exist in the material of origin will not be available in the output in any form. A more nuanced perspective could also include considerations towards salinity-nutrient ratios, carbon-nitrogen ratios, threats of contamination, as well as overall solubility of organic materials within a given timeframe. As such, categorisation can provide insight into the potential strengths and challenges that may be faced when using a variety of inputs. These categories are : i) Farm waste, ii) Industrial waste, and iii) Consumer waste, which are further sub-categorised into groups of similar nutritional composition.

3.2.1. Farm waste

Farm waste categorises low-grade horticultural products, aquaponic wastes, and animal manure as forms of "nutrient leakage". There are three main sources of farm waste : i) Animal waste ii) Aquaponic by-product and iii) Farm residue. While not strictly considered "food-waste", these inputs are by-products of food production and can be a rich source of nutrients. The concept of transporting rurally sourced farm waste for usage in urban hydroponic systems may seem inefficient, however, protected cropping is still a popular method of production in rural areas, particularly for fragile horticultural crops which require shelter from variable or unfavourable climactic conditions. Furthermore, protected systems themselves will produce waste – in the form of vegetation or defective produce which can be immediately reutilised in growing the next crop. Farm waste can be characterised as large amounts of homogenous organic matter. As a result, scalability becomes a priority when considering methods to process such vast amounts of waste. Evidence supporting a strong consideration of scalability is shown in this review, which found that 17 of the 18 papers in this review utilise some form of fermentation – a relatively energy efficient method of bioconversion relative to some of the other techniques found in this review.

3.2.1.1. Animal manure. Animal manure has been a significant source of plant nutrients throughout history, as such it has been extensively studied in on-field use, and recently interest has spread to using it as a source of nutrients for hydroponic systems. Manure is typically favoured as an on-field fertiliser as it has a rich cation exchange capacity and has all the necessary micro- and micro-nutrients required for crop growth – many studies use this as a basis for the development of hydroponic solutions utilising manure as the primary input (Tikasz et al., 2019). The infancy of this research is reflected by a large variety of variables with few replications across studies. These include the presence of additional inputs such as sugars, the presence of microbial inoculation, as well as the primary inputs themselves – a trend that repeats itself through all categories of food-waste. This leads a lot of research that is largely incomparable. This review identified 10 papers that fit within the definition of "animal manure," found that nine of them utilised manure sourced from goats (3), poultry (4), pigs (1), or unspecified livestock (1), while only one paper utilised urine (rabbit) as its primary input – justified by citing the high nitrogen content of rabbit urine (2 % N), as well as "other nutrient contents" (Guntara et al., 2021).

As a whole animal manure solutions did not produce consistent results, although the spread of methods limits the reliability of comparisons between papers. Table 3 shows that of the seven papers that utilised a mineral control solution, one was able to be considered superior to a significant degree (Tikasz et al., 2019), two were able to substitute a portion of the control without significant yield loss (Sunaryo et al., 2018; Wang et al., 2019), and one other was able to match the control without significant difference. Between these findings, it was found that there was no common factor in feedstock that consistently produced superior yields. Instead, solutions that could most replicate the nutrient profiles of the commercially available standard solutions performed the best.

3.2.1.2. Aquaponic by-product. Aquaponic systems are a variation of the organic hydroponics system. By utilising aquatic species, often fish or crustaceans, as a source of nutrients for crops in soilless growing systems. During operation, plants extract solubilised nutrients from the water column, produced by fish and mineralised by microbial populations which favour porous and well aerated locations. In addition to the solubilised ammonia produced, aquaponic systems produce a solid by-product comprised of insoluble fish and feed waste that has collected at the bottom of tanks or in filter systems. This sludge is rich in ammonia and requires aeration to begin the mineralisation of its ammonium deposits (Zhang et al., 2020). Nitrate rich sludge may not be usable in aquaponics system, as nitrates are toxic to many aquatic species, however they may be an effective nitrogen supplement in other organic hydroponic systems.

Six research papers have been found to incorporate aquaponic by-products as the primary feedstock. Five of the six papers utilise sludge, while the last utilises biofloc – the semi-solid bacterial colonies which appear at the top of aquaponic reservoirs (Raju Panggabean et al., 2020). All papers utilised either aerobic or anaerobic digestion as the processing method to optimise the nutrient content and separate solid and liquid parts. Two papers compared a FWBHF against a synthetic control solution, with results showing that there was potential in

Table 3
A comparison between the most effective treatments relative to a synthetic control. Only papers which trialled animal manure based FWBHF against a synthetic control are included.

Author	Feedstock	Substitution rate (v/v)	Treatment	Crop species	Average control fresh weight yield (g)	Average treatment fresh weight yield (g)
Abd-Elmoniem et al. (2001)	Chicken	FWBHF + AB-mix (1:1)	Anaerobic fermentation	Lettuce (*Lactuca sativa)*	873	839
Kechasov et al. (2021)	Pig manure	na	Active bioconversion of anaerobic fermentation	Tomato (*Solanum lycopersicum*)	4700 ± 900	3700 ± 1300
Liedl et al. (2006)	Broiler litter	na	Anaerobic fermentation	Lettuce (*Lactuca sativa)*	170.27	99.92
Ntinas et al. (2021)	Animal and plant based biogas	na	Biogas slurry (anaerobic)	Lettuce (*Lactuca sativa)*	249	175
Sunaryo et al. (2018)	Goat manure	FWBHF + AB-mix (1:1)	Anaerobic Fermentation	Lettuce (*Lactuca sativa)*	75.33	79.03
Tikasz et al. (2019)	Turkey manure	na	Aerobic Fermentation	Lettuce (*Lactuca sativa)*	17.5 ± 0.7	19.1 ± 2.7
Wang et al. (2019)	Poultry manure	FWBHF + AB-mix (1:1)	Biogas slurry (anaerobic)	Lettuce (*Lactuca sativa)*	204.46 ± 13.46	190.66 ± 15.47

replicating, but not surpassing, the efficacy of the control (Ezziddine et al., 2021).

Only one paper performed a comparison between processed sludge-waste against a conventional aquaponics system, Goddek et al. (2016) found that both anaerobic and aerobic treatments yielded equal to, or more effectively, than the control aquaponics system. The utilisation of an aquaponic system as a benchmark is tenuous as a reference for yield performance, as aquaponic systems tend to yield less than conventional hydroponic systems (Ayipio et al., 2019). Additionally, the cost of lowered yields is generally made up from the husbandry of aquatic species – although majority of profits from aquaponic systems are from the cultivation of crops, not fish (Greenfeld et al., 2019). In the case of *Goddek*, lettuce has been identified as one of the few species where aquaponic systems can compete in yield efficacy relative to conventional systems (Ayipio et al., 2019) – hence, the level of performance derived from the sludge-based FWBHF highlights the potential for re-utilising aquaponic byproduct, due to its capacity to replicate the efficacy of an aquaponic system (Tables 4 and 5).

Notably, all five papers based on aquaponic sludge provided nutrient analysis on the final product (Delaide et al., 2021; Ezziddine et al., 2020; Panana et al., 2021; Ezziddine et al., 2021; Goddek et al., 2016). Their research is consistent in showing that there is an adequate density of nitrogen, however macro- and micro-nutrient ratios are vastly different from the standard control solutions – with potassium deficiency being a particularly defining aspect of aquaponically based FWBHF. This nutrient imbalance is further discussed in section *3.4 Nutrient deficiencies and Solutions*.

3.2.1.3. Vegetative residue. Vegetative residue from farms is classified as the organic waste by-products generated from crop production. Research into the use of raw vegetative waste from farms is limited, with three of the four papers in this section utilising biogas digestates derived from vegetative matter. This is likely due to farm residue being regularly reincorporated back into the land it is derived from (FIAL, 2021), or that it is too costly to transport waste materials to produce hydroponic solutions without prior value extraction, such as biogas production. However, this research can be applied to reutilise vegetative by-products from hydroponic production of fruit bearing crops, such as tomatoes, which produce a large amount of unmarketable vegetative matter which must be disposed of. Thus, local, or in-house bioconversion facilities could potentially be used to reconstitute such waste into future crops.

Across the four papers included, vegetative residue included cane reed residue, pasture silage, and grape vines as a source of nutrients for a hydroponic solution. One of three treatments utilising biogas residue matched or surpassed the control. The methodology transformed the solid waste from liquid fertiliser into a substrate for hydroponic systems. The pelletised waste significantly increased fresh shoot weight compared to the rockwool (control) substrate, demonstrating the potential of solid fertilisers (Ronga et al., 2019) (Table 6).

Table 4
The comparative performance between a conventional aquaponic system and anaerobically fermented aquaponic sludge.

Author	Input	Treatment	Crop species	Average shoot weight (g)
Goddek et al. (2016)	Recirculating aquaponic system (Nile Tilapia)	na	Lettuce (*Lactuca sativa)*	92.4 ± 9
Goddek et al. (2016)	Aquaponic sludge (Nile Tilapia)	Aerobic fermentation	Lettuce (*Lactuca sativa)*	104.8 ± 15
Goddek et al. (2016)	Aquaponic sludge (Nile Tilapia)	Anaerobic fermentation	Lettuce (*Lactuca sativa)*	137.4 ± 15

3.2.2. Industry waste

Industry waste includes the by-products of food processing productions that are discarded without further use. This section includes 10 papers that includes wastewater, mushroom media waste, distillery slop, and seafood residue. Similar to the farm section, majority of the methods used are conscious of scalability, utilising non-energy intensive methods of processing. This can be attributed, again, to the homogeneity of inputs as well as the large availability of inputs. The main inputs in this section can thus be broken down into i) Wastewater and ii) Solid wastes. Within the *solid wastes* category, there is a greater level of variance in both inputs and methods compared to other sections – aligning with the expectation of increasingly individualised products that exist as the food-chain approaches consumer levels.

3.2.2.1. Wastewater. Industrial wastewater papers were selected based on the predominant input being in liquid form. This category was distinguished from solid wastes as the state of matter may influence the rate of precipitation, mineralisation, or a range of other processes that can influence nutrient availability, equipment functionality, and mineralisation rate during any treatments between waste collection and hydroponic use (Grzyb et al., 2020a, 2020b). Of the five papers included, two source their constituent wastewater from tofu production, one from a brewery, the other from molasses production, and the last is by-product from corn wet milling. Like farm-based treatments, most wastewater-based treatments utilised anaerobic digestion to mineralise nutrients into inorganic forms. There is limited understanding as to whether the liquid state of these by-products alters the pathways organic nutrients undergo to transform into plant available form.

Overall, wastewater-based solutions performed well relative to their

Table 5
A comparison between the most effective treatments relative to a synthetic control. Only papers which trialled aquaponic-waste based FWBHF against a synthetic control are included.

Author	Feedstock	Substitution	Treatment	Crop species	Average control fresh weight yield (g)	Average treatment fresh weight yield (g)
Ezziddine et al. (2021)	Aquaponic sludge (Brown Trout)	Na	Aerobic fermentation	Lettuce (*Lactuca sativa)*	243 ± 30	203 ± 40
Delaide et al. (2021)	Aquaponic sludge (Pikeperch)	Na	Aerobic fermentation	Lettuce (*Lactuca sativa)*	650	500
Delaide et al. (2021)	Aquaponic sludge (Pikeperch)	Supplemented NPK to 1, 1.8, and 4.5 mmol/L	Anaerobic fermentation	Lettuce (*Lactuca sativa)*	600	580

Table 6
A comparison between the most effective treatments relative to a synthetic control. Only papers which trialled vegetative farm waste based FWBHF against a synthetic control are included.

Author	Feedstock	Substitution rate (*v*/v)	Treatment	Crop species	Average control fresh weight yield (g)	Average treatment fresh weight yield (g)
Ntinas et al. (2021)	Animal and plant-based biogas	Na	Biogas slurry (anaerobic)	Lettuce (*Lactuca sativa)*	249	175
Lind et al. (2021)	Crop residue, plant-based food waste, iron chloride	Na	Biogas slurry (anaerobic)	Bok choy (*Brassica rapa* var. *chinensis)*	175	140
Ronga et al. (2019)	Maize silage, triticale silage, cow slurry, grape stalks	Substrate replacement	Biogas slurry (anaerobic)	Lettuce (*Lactuca sativa)*	0.64 (dry weight)	0.82 (dry weight)

respective controls. Of the four papers with synthetic control solutions, all included at least one treatment which, on its own or substituting a portion of the conventional solution, statistically matched or surpassed the efficacy of the control. Differences in reporting methods are apparent in this grouping of papers. The metrics utilised to measure the yield outcomes of a solution include the dry leaf or shoot weight, fresh weight, and stem height. In addition, liquid waste suffers from an unfavourable salt to nutrient ratio, which will be further discussed in section *3.5 Salinity and Sodicity* (Table 7).

3.2.2.2. Solid wastes. Solid wastes in the context of industrial waste encompasses a wide range of sources. It can be distinguished from liquid waste by the presence of a substantial amount of solid material when dried. Six papers were collected in this section. Two utilise fishery waste, one uses sugar cane leaves and ethanol slop, another uses mushroom substrate waste, another uses cow paunch waste, and the final paper utilises a wheat bran-based compost to release nutrients over time. There are deviations from traditional digestate methodologies here, with the drying and powdering of crab shells (Sawain et al., 2020), as well as the development of a hydroponically suitable nutrient substrate (Tong et al., 2021). The solid waste section marks a transition in processing techniques, where scalability is often deprioritised for more novel, exploratory methodologies.

Despite the absence of shared feedstocks and methodology, both trials with synthetic controls matched the efficacy of their relative solutions. These findings highlight the importance of processing steps between obtaining food-waste and utilising it as FWBHF. Replication in this area is limited, as *solid industrial waste* hosts a wide array of novel inputs and methodologies which define the transition of FWBHF development as food-waste sources transition towards consumer level waste (Table 8).

3.2.3. Consumer waste

Consumer waste includes the by-products and waste produced by retail, food industry, or end-users of the food production chain. In high-income countries, UNEP (2021) reported that 61 % of waste at this level was produced by households, with retail and food services generating the remaining 39 % of waste. This section includes nine papers that study a wide range of treatments applied to food-waste that come from a variety of sources. These papers are rarely similar, and unlike previous sections, are much more varied in both treatments and inputs. Feedstock specificity ranges from homogenous end-stage food, like sea lettuce and

Table 7
A comparison between the most effective treatments relative to a synthetic control. Only papers which trialled industrial wastewater based FWBHF against a synthetic control are included.

Author	Feedstock	Substitution rate (*v*/v)	Treatment	Crop species	Average control comparison metric	Average treatment comparison metric
Anggraini et al. (2020)	Tofu wastewater	na	Anaerobic fermentation	Lettuce (*Lactuca sativa*)	14.8 cm (stem height)	14 cm (stem height)
Chaorlina et al. (2021)	Tofu wastewater	FWBHF + AB-mix (1:2)	Anaerobic fermentation	Lettuce (*Lactuca sativa*)	3.46 g (fresh weight)	5.73 g (fresh weight)
Figueroa et al., 2015	Anchovy fishmeal wastewater	na	Anaerobic fermentation	Red Bean	6 cm (stem height)	7 cm (stem height)
Kano et al. (2021)	Corn steep liquor	na	Raw	Bok choy (*Brassica rapa* var. *chinensis)*	6.51 g (dry leaf weight)	6.12 g (dry leaf weight)
Li et al. (2020)	Molasses wastewater	FWBHF + AB-mix (1:19)	Anaerobic fermentation + reduction	Canola (*Brassica napus L. 'Zhongshuang 11'*)	0.14 g (dry weight)	0.22 g (dry weight)
Riera-Vila et al. (2019)	Brewery wastewater	na	Raw	Lettuce (*Lactuca sativa*)	2.83 ± 0.1 (dry plant weight)	0.46 ± 0.1 (dry plant weight)
Riera-Vila et al. (2019)	Brewery wastewater	na	Anaerobic fermentation	Lettuce (*Lactuca sativa*)	2.83 ± 0.1 (dry plant weight)	2.09 ± 0.5 (dry plant weight)

Table 8
A comparison between the most effective treatments relative to a synthetic control. Only papers which trialled industrial solid-waste based FWBHF against a synthetic control are included.

Author	Feedstock	Substitution rate (v/v)	Treatment	Crop species	Average control comparison metric	Average treatment comparison metric
Churilova and Midmore (2019)	Paunch waste	na	Vermiculture	Pak Choi (*Brassica chinensis* L. cv. Shanghai)	9394 g/m^2 (fresh shoot weight)	7244 g/m^2 (fresh shoot weight)
Phibunwatthanawong and Riddech (2019)	Molasses, distillery slop, sugarcane leaves	na	Anaerobic fermentation	Lettuce *(Lactuca sativa)*	2.33 g (shoot fresh weight)	2.42 g (shoot fresh weight)
Tong et al. (2021)	Wheat bran, oil cake, chicken manure	na	Compost	Bell peppers (*Capsicum annuum*, L.)	7.6 ± 6.5 cm (plant height)	6.1 ± 2.4 cm (plant height)

tomatoes, to non-specific ratios of food-waste from restaurants. A key distinction between food-waste at consumer levels and previous levels is the unique blend of processed and unprocessed products that have been altered from their original form with salts, oils, seasoning, and sauces. This poses as the crux of transforming consumer food-waste into a viable hydroponic solution. The transformation of such non-homogenous, fatty, and salty produce into a solution fit for plant uptake has proven to be a challenge – often presenting as overly saline solutions (Siddiqui et al., 2021).

Generally, research in this category is largely incomparable due to the difference in methodology and inputs. The methodologies included tend towards more novel techniques which do not prioritise scalability. These methods produced a range of results; of the 5 papers which included a suitable control, one surpassed the control, while two more were able to substitute a portion of the solution without losing effectiveness. (Table 9).

3.2.4. *Reflection on feedstock*

As the feedstock source nears the consumer, variability in inputs and methods become increasingly exaggerated, highlighting a fundamental consideration for future research. Consideration for the importance of scalability is critical to the economic viability of developing hydroponic solutions, but the exploration of novel methods can be beneficial to develop niche solutions adapted to more specific conditions set by input material or environmental constraints. For example, Kawamura-Aoyama et al. (2014) utilised a method where the final product was a powdered product. While the method required additional steps of dry-freezing and milling, the extra energy costs produced a powdered fertiliser that provides opportunities aqueous solutions may have difficulty overcoming. These benefits may include shelf-stability, transportability, and replicability. This lowers logistical costs required to ensure solution stability and allows for an inert base that is receptive to modification without additional biological activity.

It is clear that methodology is a key player in developing a successful fertiliser, however it should be emphasised that feedstock plays a similarly important role on the outcome of a solution. This can be seen by comparing the nutrient profiles derived from two similar vermicompost based solutions. Despite the similarities in method, the solutions produced by Churilova and Midmore (2019) and Loera-Muro et al. (2021) differ greatly. Table 10 shows differences in the "EC : Available nitrogen" ratios, of which *Loera-Muro*'s study had a more optimal concentration. The relevant factors which may have influenced outcomes include differences in time before flushing, pre-composting, and feedstock.

Without additional research, it is unclear which of these factors is plays a predominant role in improving available nitrogen relative to EC. With considerations for other known actors in nitrification, it may be

Table 10
A comparison between two vermiculture based solutions.

	Churilova (2019)	Loera-Muro (2021)
EC: Available N (ds/cm: mg/L)	1: 88	1: 526
Time in vermiculture (days)	70	84
Inputs	Cow paunch material	Kitchen waste (50 %), animal manure (50 %)

Table 9
A comparison between the most effective treatments relative to a synthetic control. Only papers which trialled consumer-based FWBHF against a synthetic control are included.

Author	Feedstock	Substitution rate (*v*/v)	Treatment	Crop species	Average control comparison metric	Average treatment comparison metric
Bergstrand et al. (2020)	Organic household waste (37 %), manure (31 %), slaughter residues (19 %), other organic food waste (13 %), iron chloride (0.03 %) based biogas	na	Aerobic fermentation	Pak Choi (*Brassica campestris v. chinensis*)	113.6 g (fresh weight)	60.43 g (fresh weight)
Churilova and Midmore (2019)	Industrial kitchen waste	na	Vermiculture	Pak Choi (*Brassica chinensis* L. cv. Shanghai)	9394 g/m^2 (fresh shoot weight)	9611 g/m^2 (fresh shoot weight)
Hilman et al. (2021)	Vegetables	1:1	Anaerobic fermentation	Mustard greens (*Brassica juncea* L.)	29.24 g (fresh weight)	41.79 g (fresh weight)
Giménez et al. (2020)	Tomato (71 %), Onion (17 %), Vineyard residue (12 %)	na	Compost	Lettuce (*Lactuca sativa)*	2.22 ± 0.05 g (fresh biomass)	2.00 ± 0 g (fresh biomass)
Kawamura-Aoyama et al. (2014)	Fish (33 %), vegetables (33 %), café food waste (33 %)	na	Powdered	Lettuce (*Lactuca sativa* var. *capitata)*	16.7 ± 6.1 g (fresh shoot weight)	15.4 ± 4.3 g (fresh shoot weight)
Loera-Muro et al. (2021)	Kitchen waste (50 %), animal manure (50 %)	na	Vermiculture	Mint (*Mentha spicata)*	1.6 ± 0.5 g	3 ± 0.5 g
Loera-Muro et al. (2021)	Kitchen waste (50 %), animal manure (50 %)	na	Vermiculture	Rosemary (*Rosmarinus officinalis)*	4.5 ± 1 g (fresh shoot weight)	5.2 ± 4.9 g (fresh shoot weight)
Yusuf et al. (2021)	Seaweed (*Ulva Lactua*)	na	Boiled	Lettuce (*Lactuca sativa)*	8.39 g (fresh weight)	2.23 g (fresh weight)

sensible to suggest that the determining factor in the disparity between the two solutions can be attributed to the presence of cow manure. Compared to cow paunch material, manure tends to have a naturally higher nitrogen content. However, it is difficult to entirely attribute the elevated N in *Loera-Muro's* solution to the manure itself entirely, as it only composes 50 % of the feedstock. The other 50 %, identified as "kitchen waste" highlights one of the obstacles facing research on consumer-level waste-based solutions. The variety of food preferences around the world causes broad terms such as "kitchen waste" to be vague in identifying the constituent feedstocks of a solution – although at larger scales this sort of sorting may be impossible to achieve.

The large spread of inputs and methodologies provides two approaches to exploring existing literature. It was determined that grouping by methodology was a more effective way to examine trends in the research area. Ultimately, the infancy of the research limits the scope of this review to understanding the effect certain methodologies have across a spectrum of inputs, as opposed to the understanding of the reactions of specific inputs to niche methods.

3.3. Methodology and limitations

Methodology is the primary factor researchers influence within FWBHF research. This review defines methodology as the application of processes which prepare, facilitate, or alter the bioconversion of food-waste into FWBHF's. Current knowledge attributes the underlying success of a methodology to biological activity, highlighted by Fig. 2, which identifies aerobic and anaerobic fermentation as the most popular method trialled. Fermentation, or digestion, is the breakdown of organic matter into inorganic compounds using microorganisms – a process which is essential to nutrient cycling in natural systems (Garcia and Kao-Kniffin, 2018). While variable, bioconversion methods can be guided with a range of tools to enable the replication of results when utilising a fixed feedstock. Confirming the theory that identical methods will produce the same results is an essential element in the continued development of FWBHF's. Adhering to this assumption, this section covers the distribution of methodology across the literature included in this review and attempts to identify the associated strengths and weaknesses attributed to each method of FWBHF production.

By far, the most frequently used methodology was digestion, with 26 out of the 37 reviewed papers utilising some form of fermentation. Fermentation was distinguished into aerobic, anaerobic, and novel forms due to the distinct differences in their mechanisms and outputs. A brief comparison between aerobic and anaerobic processes reveals that the primary difference is the presence of oxygen in the solution during the process. This absence of oxygen limits the respiratory activity from microbial populations, creating two drastically different microbiomes. The microbiomes deviate in process after initial glycolysis, where oxygen availability dictates the continuation of metabolic processes such as NAD+ generation and nitrification. In anaerobic settings, these do not occur and are replaced with less energetic interactions which produce ethanol or lactic acids (Buckel, 2021a, 2021b).

Thus, when considering the impacts aerobic and anaerobic digestion have on organic matter, the processes of carbon breakdown and nitrogen mineralisation are the most impacted by the availability of oxygen. Carbon compound breakdown deviates after initial glycolysis, where pyruvate acids are either aerobically metabolized into CO2 and H2O, while anaerobically fermented pyruvate compounds produce either ethanol or lactic acids (Melkonian, 2021). Whether ethanol or lactic acids are produced is dependent on the resident microbial community – inoculations of fungal yeasts or bacterial *Lactobacillus,* respectively, can be used to dictate the output (Tristezza et al., 2016). Nitrogen mineralisation, similarly, requires oxygen as an electron acceptor after anaerobic processes break organic nitrogen into ammonium (NH4+). Without oxygen, nitrates (NO3-) cannot be synthesized, and the resulting solution could be unviable due to risks of ammonium toxicity (Buckel, 2021a, 2021b).

Other elements, such as potassium and phosphorus do not directly utilise oxygen to become plant available. Phosphorus is often more available in flooded conditions, as the hydrolysis of phosphate compounds solubilizes inorganic phosphates – a process not limited by oxygen availability. Potassium availability is minimally influenced by anoxic environments as K exists predominately in inorganic form. Potassium ion availability is still primarily determined by the rate of organic breakdown (Fageria et al., 2011). Instead, the pH of the solution is important in determining the availability of plant macro- and micronutrients. Generally, a pH between 6.5 and 7 is preferred for majority of horticultural crops in hydroponic systems. While there are exceptions, this range provides the greatest variety of plant available nutrients. A slightly acidic solution solubilizes iron, zinc, boron, manganese, and copper which are unavailable in alkaline conditions.

Both aerobic and anaerobic methods of digestion create solutions that tend towards a lower pH. This is the result of either lactic acid production or through the formation of carbonic acids from dissolved carbon dioxide found within the solution. Generally, anaerobic solutions tend to have a more acidic base compared to aerobic pathways. This is attributed to the increased availability of H+ ions produced by lactic acid pathways (Abedi and Hashemi, 2020) as well as the tendency for aeration to displace dissolved CO2 (Colt and Kroeger, 2013a, 2013b). The absence of oxygen tends to limit energetic respiration – preventing excessive volatilization and preserving a greater density of nutrients

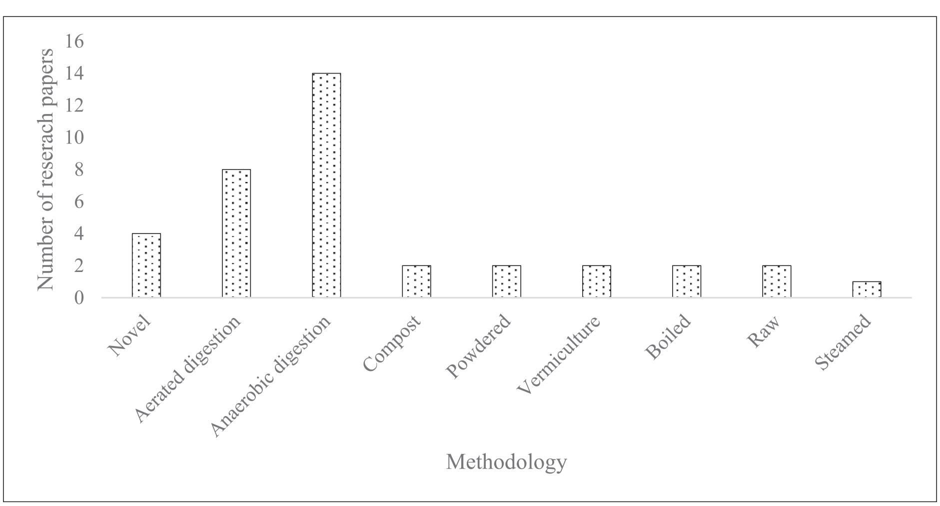

Fig. 2. The distribution of methodologies utilised by the selected research papers (n = 37).

within the solution.

Despite the clear functional similarities between aerobic and anaerobic systems, the difference in outputs distinguishes the two as entirely separate methodologies. This has led to exploration into methodologies which exploit the benefits of both processes. These novel methods are either semi-aerated or multi-step. These systems are capable of altering their microbiota through populations of “facultative species” which can tolerate limited oxygen environments and exist on a spectrum between strictly aerobic and anaerobic species. They are ubiquitous across all but the strictest fermentation methods. Thus, with the understanding that there is no such thing as an entirely aerobic or anaerobic population, this paper differentiates between aerobic and anaerobic fermentation based on i) deliberate and stated intentions, ii) actions that result in a certain population being supported, and iii) final nutrient compositions.

The remaining methods, lack the interdisciplinary interest of traditional fermentation techniques. As a result, the specific microbial, chemical, and physical mechanisms of organic matter breakdown represent a significant gap in knowledge. Instead, based on provided nutritional analysis and diagnostic information, the next sections of this review will describe the limitations which face existing FWBHF research.

3.4. Nutrient deficiency and solutions

Plant available nutrients is first and foremost, dictated by the concentration of a given element within a hydroponic solution. Whether an element is present or absent can be attributed to an array of factors. This review has identified commonalities across studies that may have led to an impact on the availability of micro- and macro-nutrients. This section will explore the challenges and solutions that affect organic solutions.

As stated before, the unavailability of oxygen in anaerobic systems limits the mineralisation of ammonia. This can lead to an imbalance between nitrates and ammonia – causing a deficiency in plant available nitrogen while risking ammonia toxicity. This behaviour is evidenced across several studies, with Tikasz et al. (2019) finding that an aerated turkey manure produced a superior fresh harvest weight compared to a synthetic control. The methodology involved the aeration of various manures for 1.5 days. While the turkey solution was the only treatment to surpass the control solution, this was unlikely the result of a superior feedstock. The success of this solution could be attributed to the collection method of the turkey waste – which left it resting for six months prior to intentional fermentation. This resting period is likely to have allowed for a more complete mineralisation compared to the 1.5-day aeration period all other treatments were given. Investigation of the nutrient analysis shows that the successful turkey treatment had an NO3:NH4 ratio of approximately 10:9, while the best performing chicken treatments had a ratio of 3:350.

This prompts questions into the ideal time required for complete mineralisation of organic nitrogen into inorganic forms. While prolonged periods of fermentation ensure total mineralisation of organic nitrogen, the quandary in this practice is that there is evidence that would suggest prolonged fermentation of any sort can lead to the eventual loss of other key nutrients. This behaviour is observed across several studies. Riera-Vila et al. (2019) compared raw and anaerobically digested brewery wastewater in a growth trial. A comparison of the two solutions shows an N:P content of the raw solution contained 7: 80 (mg/L), while the digested solution contained 170: 22 (mg/L). The increase in nitrogen is the result of supplementary ammonium nitrate, however the phosphorus content has decreased to only 25 % of its original content. This is consistent with existing research, which shows that prolonged aeration of a solution increases alkalinity, which reduces soluble P by up to 75 % within the first 24 h (Zhu et al., 2001a, 2001b). This sort of degradation is tolerable for phosphorus, as the ratio of phosphorus required relative to nitrogen is significantly less demanding than the ratio of nitrogen to potassium.

Potassium degradation in extended fermentation periods was not observed in any study. Phibunwatthanawong and Riddech (2019) performed nutrient analysis at multiple stages of fermentation, between day 15 and 30 potassium availability was stable. Although, literature suggests that continued fermentation after ammonium has been converted to nitrates may cause a reduction in available potassium. This can be attributed to the conversion of positively charged ammonium molecules into negatively charged nitrates - shifting the microbial community into favouring denitrifying micro-organisms such as *Bacillus* and *Pseudomonas* which require an electron donor to reduce nitrates into nitrites (Shukla et al., 2021). Studies into the optimisation of *Bacillus* shows that potassium improves the rate of exopolysaccharide production – a proxy for the rate of metabolism (Lee et al., 1997). This suggests that there is an optimal timeframe for anaerobic fermentation. The premature usage of a solution risks nitrogen deficiency or ammonia toxicity, while an excessive fermentation period may lead to deficiencies in other key macronutrients. Further research may be necessary into the exploration of an ideal timeframe for the efficacy of nitrogen mineralisation in relation to the plant availability of phosphorus and potassium.

In order to compensate for nutrient deficiencies, there are a range of solutions that have been explored. Outside of altering the direct inputs, alternative methods of nitrification, as well as the use of organic and synthetic supplements have been trialled. A potential solution to balancing potassium degradation alongside nitrification is explored in Lind et al.’s (2021) trial. This method utilises an integrated nitrification reactor, which actively mineralises raw biogas digestate during the growth period of hydroponic crops. Using this method of “active nitrification,” an appropriate NPK ratio of 18:4:25 was able to be established at the beginning of the growth trial. With active nitrification and specific pH management, the treatment was able to meet the yield outcomes of the synthetic control when given an additional week of growth. This delayed vegetative growth may be symptomatic of a nitrate bottleneck caused by the limitations of an active conversion process. Maintaining a more neutral environment is essential, as an acidic environment generally inhibits the nitrification process (Tarre and Green, 2004). This suggests the active conversion process may be limiting the available nitrogen content. It may be worth further study to into a two-part system, which uses a pre-fermented solution in conjunction with an active fermentation system to optimise macro-nutrient release and availability.

Alternative methods of “active nitrification” have also been explored by Kawamura-Aoyama et al. (2014) and Tong et al. (2021). While neither utilise fermentation methods, both strive to supply the necessary nutrients through the use of microbial activity in slower ways that accommodate for perennial crop species. Tong et al. (2021) explores the potential of utilising a bokashi compost substrate as a method for introducing nutrients into a hydroponic system. This method relies on the eventual conversion of nutrients from within a bio-active compost to provide the necessary resources required for efficient plant growth over time. The compost was made from a combination of wheat bran, oil cake, and chicken manure with an intentional inoculation of a microbial starter. This method proved to return superior yields relative to the direct application of the compost leachate. This could be due to the benefits of having a delayed release of phosphorus and potassium – which encourage flowering, while early on availability of N would increase vegetative growth prior to the reproductive stages of the crop. By emulating a rich soil, the substrate is able to release nutrients in a controlled fashion while maintaining a stable microbiome for the crop rhizosphere. This biome could manage nitrifying bacteria which prevent diseases as well as optimise nutrient uptake relative to the exposed roots of traditional hydroponic systems. The use of microbial actors to promote plant growth will be further discussed in *3.6 Microbial Activity*. The only compost treatment tested was a 40–40-10 combination of perlite, coco coir, and the bokashi compost. Future studies should alter ratios and accompanying substrates to optimise the release of nutrients over time and in appropriate quantities.

Kawamura-Aoyama et al. (2014) adopts a “slow release” philosophy like Tong et al.'s (2021) bokashi compost. By drying and powdering a combination of meat, vegetables, and café food-waste, the treatment involves a daily dose of powder each day to produce the necessary nitrogen required for plant growth. The nitrifying population resides in a bag of tree bark, and other macro- and micro-nutrients are synthetically supplied. A key difference between the two studies is the system type used. *Tong* utilises drip irrigation, while *Kawamura* adopts a floating system. Drip irrigation benefits from relying on the retentive capabilities of its substrate to maintain an appropriate environment for plant roots, conversely floating systems involve the complete submersion of a plants roots into the growing solution. *Kawamura* found that without active water movement, yield outcomes between the treatment and the control were significantly different. The addition of water movement may encourage nitrification through aeration or prevent pest and diseases from establishing. The nature of these slow-release technique is ideal for perennial, fruiting crops such as tomatoes. The slow release of nitrates over time does not lead to excess vegetative growth and thus inhibiting flowering or fruit development.

As observed in Kawamura-Aoyama et al. (2014) study, the development of organic solutions is not constrained to the function of being an "all-in-one" solution. Many papers seek to determine if additions or substitutions can assist growers in achieving yields similar to commercial fertilisers. The ability for a solution to function independently of supplementation varies from study to study – although feedstock is generally the primary determinant of which supplements a solution will ultimately need. For example, potassium deficiency is a frequent occurrence in aquaponic systems, as marine species primarily produce nitrogenous based waste, and as such synthetic additions of potassium are often added to compensate for the missing element (Yep and Zheng, 2019). This deficiency was observed across all 5 papers that utilised fish based aquaponic sludges as a primary feedstock.

Table 11 shows an imbalanced NPK ratio observed across all papers that utilised fish-based aquaponic sludges as a primary feedstock. Future research in this area can explore methods to compensate for the low inherent potassium content. Another concern surrounding aquaponic based fertilisers is the presence of heavy metals, such as cadmium, lead, and mercury. *Ezzidine* utilises chitosan, a metal chelator derived from the carapaces of ocean crustaceans as an organic method of managing heavy metals without reducing concentrations of metals necessary for plant growth. Chitosan was also utilised by Sawain et al. (2020). *Sawain* explored the calcium rich carapace of crab shell as a supplement to an aquaponics system. When crushed and mixed in with manure, the resulting sludge significantly improved watercress wet weight without affecting the survival rate of catfish over a 30-day period. The direct effects of chitosan have not been isolated in hydroponic or aquaponic systems. As such, the nutritional contribution of chitosan requires additional investigation, as it is largely insoluble at neutral and higher pH levels.

To achieve optimal levels of nutrients, both organic and synthetic supplementation can be utilised. Sunarya et al. (2020) anaerobically fermented mushroom production casings, known as baglog, to produce a solution which, while sufficient for growth, did not have the required level of nitrogen for an optimal yield. The study supplemented the baglog with cow manure and banana peels, improving the NPK ratio from 10:4:13 to 14:7:23. Similarly Arshad et al. (2018) utilises banana peels to supplement K in a goat manure-based solution. Neither solution was trialled in growth systems, however, nutritional analysis expresses the potential to supplement a fertiliser with other products to optimise its composition.

Table 11
The NPK ratios from 7 FWBHF's which utilised the fermentation of aquacultural waste.

Author/s	Species	Method	NPK ratio
Ezziddine et al. (2020)	Salmon	Aerobic Fermentation	9–1–1
Ezziddine et al. (2020)	Salmon	Aerobic Fermentation	90–16–13
Ezziddine et al. (2021)	Brown Trout	Aerobic Fermentation	62–18–11
Panana et al. (2021)	Pikeperch	Aerobic Fermentation	12–19–2
Delaide et al. (2021)	Pikeperch	Aerobic Fermentation	11–0.1–0.3
Goddek et al. (2016)	Nile Tilapia	Aerobic Fermentation	53–3–17
Goddek et al. (2016)	Nile Tilapia	Anaerobic Fermentation	56–3–16

Synthetic remediation presents itself as a more reliable and convenient option. Liedl et al. (2006) found that ammonia toxicity caused by a poultry-based treatment resulted in tomatoes with fewer and smaller fruits. This was remedied by the supplementation of calcium nitrate, improving the nitrate-ammonia balance – leading to the recovery and improved performance of the crop. Other nutrient deficiencies, such as magnesium deficiencies were also discovered, and were remedied by a foliar treatment of magnesium sulphate – boosting yields to meet that of the control treatment. An extension of this remediation would be to simply substitute portions of commercial solutions.

While not a complete replacement, the reduction of use in mineral fertilisers can still create significant impact. Of the 11 papers which trialled substitution, 10 were able to substitute a portion of the control solution to the point where there was no significant loss in yield performance. The range of trialled substitute tends to range between 20 % up towards 80 %. The highest rate of substitution without significant loss in yield was observed by Anggraini et al. (2020) at 66 %, utilising an anaerobically digested tofu wastewater. In particular, Kawamura-Aoyama et al. (2014), Abd-Elmoniem et al. (2001), and Al-Mehadee and Sarheed (2021), found that supplementing the nitrogen provided by organic sources with synthetic P, K, and micronutrients was an effective strategy in maintaining yield performance relative to the control.

The benefit of substitution alleviates dependency on mineral solutions, reutilises food-waste, and improves producer resilience to fluctuations in the quality and availability of organic nutrient. Siddiqui et al. (2021) found that seasons affected the availability of certain nutrients found at the fruit market. In the winter season, phosphorus deficiency was noticed, with the produced solution having an NPK of 12–1–35, compared to spring solution ratio of 2–1–8. This seasonal difference introduces another dimension of consideration when designing food-waste based hydroponic solutions. There will inevitably be seasonal preferences for certain food-products based on price, consumer demands, or supply availability – highlighting the importance of resilient production techniques. The aforementioned substitution allows producers to incorporate organic sources of nutrients into their solutions, providing a more stable source of nutrients for their crops while contributing towards a more environmentally friendly production method.

Substitution, however, presents its own set of challenges. Economically, adoption of substitutive solutions may have limited cost efficiency, as the organic component of a conventional-organic hybrid solution may be more expensive. Furthermore, partial substitution of a solution may inhibit the availability value-adding labels such as "organic". Scientifically, it may be difficult to produce a solution with bioactive components to interact with raw, soluble nutrients. There is a risk that the sudden introduction of nutrients from synthetic solutions may encourage eutrophication or the propagation of pests and disease (Schwarz and Gross, 2004).

3.5. Salinity and Sodicity

A dense pool of accessible nutrients is key for a successful yield, however there must be considerations towards the salinity of a solution. The balance between nutrient availability and salinity is critical in a viable nutrient solution. Salinity is measured by electrical conductivity (EC) and suggested optimal levels are contentious. Generally, however, tolerable levels of EC range from 0.9 to 2.5 dS/m in hydroponic solutions for leafy greens (Ding et al., 2018). If the salinity exceeds a plants tolerance level, osmotic adsorption of minerals through the roots of a plant may be inhibited (Hosseini et al., 2021). As such, the three key parameters that must be observed are nutrient levels, pH and EC. While the three share many interactions, none are strictly dependent on one another – with means of independent adjustments for all three factors.

Managing salinity has been identified as a particularly difficult challenge in the development of food-waste based solutions. This is attributed to the addition of salts in cooking, as well as the high levels of naturally occurring sodium in protein rich waste, such as meat. This section explores sources of salinity as well as strategies to manage and maintain efficacy in the face of excessive salinity. Of the 37 papers reviewed, 19 provided undiluted EC values for their trialled solutions – allowing for the development of Fig. 3, which shows the distribution of total nitrogen relative to EC (TN:EC) separated by feedstock type. The importance of this relationship is predicated upon the osmotic capacity of nutrient adsorption based on the salinity of a solution. As EC increases, the osmotic potential of a plant decreases, causing nutrient deficiencies in a crop – regardless of the nutrient content within the solution.

Each solution has been standardized to represent a nitrogen content when EC is set to 1, and benchmarked against a standard Hoagland's solution, which when at an EC of 1.6 provides approximately 210 mg/L of inorganic nitrogen.

Excess salinity is found across a range of processing methods, from digestion, to boiling, and steaming. Although some crops are more salt tolerant than others, common hydroponic species, such as leafy greens, have lower salinity tolerances compared to other species (Albornoz and Heinrich Lieth, 2015). Seemingly, the predominant factor in solution salinity is the input, as shown in Fig. 2.

When allotted into "Farm", "Industry", and "Consumer" categories, clear distinctions between groups can be made. Referring to Table 12, there is a marked difference in between feedstock sources. The average TN:EC ratio drops is similar across all but consumer level inputs. While the standard deviation is high, relative to the mean, the average TN:EC ratio is distinctly different in consumer-based solutions. This trend could be explained by the nature of feedstock, as farm and industrial level inputs tend to be unrefined and unreduced byproducts. An acceptable ratio of TN:EC is achieved when a crops nutrient needs are met without surpassing its inherent tolerance of salinity.

A closer examination at consumer-based solutions finds two studies which provide insight into the skewed balance. 2 papers specify the usage of restaurant or café waste. Siddiqui et al. (2021) utilises waste from a service club, and a fruit and vegetable market across several seasons. This research isolates the relationship between feedstock and salinity. All feedstock types were steam heated, ground, minced, and strained to produce a liquid fertiliser. While the solution was not utilised in any growth trials, nutrient analysis found differences between the N – P – K – Na ratios of the treatments. The spring fruit market produced a ratio of 2–1–8–1, whilst the service club treatment had a ratio of 4–1–12–17. This is likely due to the "pub style" foods, with steak, hot potato chips, chicken schnitzel, gravy, and an assortment of seasoned vegetables. This reflects the importance of constituent materials in managing salinity.

Table 12
The Total Nitrogen:Electrical conductivity ratios categorised by feedstock source.

	TN:EC (x:1.6) (mg/L: ds/m)				
	Farm (*n* = 17)	Aquaponics (*n* = 3)	Industry (*n* = 7)	Consumer (*n* = 4)	Consumer + Farm (n = 4)
Mean	140	81	96	60	310
SD	119	36	67	83	307
Median	126	94	102	16	132

In terms of methodology, boiling distinguished itself as a particularly inefficient method of developing an effective solution. Arshad et al. (2018) boiled goat manure mixed in with banana peels until a 20 L vat of liquid was reduced to 5 L. The nutrient profile derived from this produced a solution with an TN:EC ratio of 1:3. A study by Yusuf et al. (2021) explored the potential of sea lettuce (sp. *ulva lactuca)*, after it had been heated up to 70 °C and strained. While there was no available nutrient profile, the solution was dosed to reach a TDS of 560, 800 and 900 ppm based on the growth stage of the lettuce crop. None of the treatments could meet the efficacy of the control. It is likely that simply boiling organic material does not extract adequate available nutrients. Future research should continue exploration into the effects boiling has on nutrient extraction and if there is potential to avoid the excess salinity produced by liquid reduction.

Just as important as the ratio between nutrients and salinity, is the total saturation of an element. Bergstrand et al. (2020) aerobically fermented a combination of manure, slaughter residues, and "other organic food-waste," which was diluted and dosed at rates where EC (ds/m) was equal to 1, 2, and 4. Notably, the solution with an EC of 1 was the closest to emulating the yield efficacy of the control. The control had an EC of 2, and unusually, the organic trial with the equivalent EC did not perform as well. While all 3 trials have a linearly increasing NO3, there is also a linear increase in NH4. Ideally, a 3:1 ratio of NO3 to NH4 is preferred, with low levels of ammonium toxicity being alleviated by the presence of nitrates (Du et al., 2021; Zhu et al., 2001a, 2001b). The control solution contained a ratio of NO3:NH4 of 21:6, while the organic solution, at all application rates, was closer to 6:5. It is possible that the increase

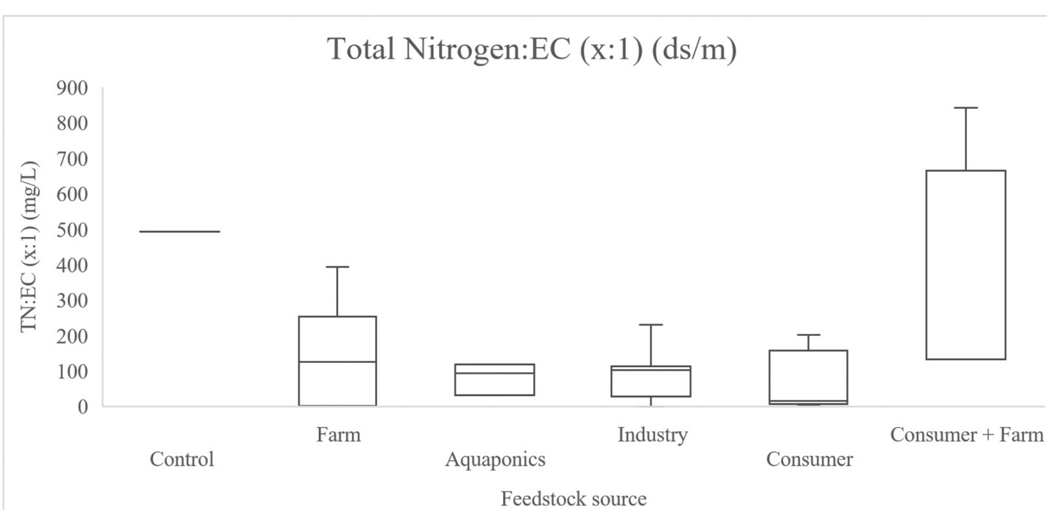

Fig. 3. Total Nitrogen:EC ratio across feedstock sources.

in total available nutrients may have led to a concentration of ammonium that inhibited plant growth.

A final consideration is that solutions with excessive EC still have potential functionality as supplements. For example, Li et al. (2020) produced condensed molasses soluble (CMS), a solution derived from anaerobically fermented molasses wastewater with an undiluted EC of 23ds/m. Even when diluted, the ratio of NPK to EC cannot accommodate plant production. Despite this, a minor supplement of 100 mg/L of condensed molasses soluble (CMS) at the seedling stage was found to enhance the growth of canola to a significant level when used in conjunction with inorganic fertilisers. This improvement could be due to the deposition of early nutrients, although it may also be attributed to microbial activity in the rhizosphere and solution. Alternatively, the density of nutrients provides a promising research area for desalination projects to improve the viability of wastewater reutilisation. Although technology has improved over time, current commercial technologies are limited to the removal of all mineral elements – including nutrients – from a solution using reverse osmosis technology. Even so, the operation of such machinery at an industrial scale would require excessive amounts of capital and ongoing funding (Ang et al., 2019). Current research into selective reverse osmosis techniques show that there is potential in the future for such technology to be available (Han et al., 2022).

3.6. Sub-system types and growing techniques

Food-waste based solutions have different demands relative to conventional solutions, evidenced by the unanimous success of the control solutions in the studies included in this review. Sub-system and nutrient application techniques have an unmeasured impact on the success of a given organic solution. As such, there are no links between subsystem types, nutrient application methods, and the yield outcome of any organic fertilisers.

In total, 7 different sub-systems were identified *i)* Ebb and Flow (EF), ii) Nutrient Filter Technique (NFT), iii) Deep Water System (DW), iv) Wick System, v) Floating System, vi) Drip irrigation System (DI). NFT systems were the most used systems (*n* = *13,* Fig. 4), with other systems having a rate of usage between *n* = *6* and *n* = *1*.

The low number of replications across the range of system types limits the comparability between literature. Hence, statistical analysis correlating system types with yield outcomes based on the identified literature in this review is unreliable. External literature comparing the effects of different system types is limited. Within this review, 35 of the 37 papers reviewed utilised one form of hydroponics system. The outliers, Churilova and Midmore (2019) and Giménez et al. (2020), compared the performance of conventional and organic solutions across two system types: DWS and DIS.

Giménez et al. (2020) utilised a compost-based solution on the growth of baby lettuce in DW and DI systems. Both systems produced statistically similar fresh weight yields to the control. The DW system averaged a slightly higher yield, with an approximate 10 % greater fresh weight (DW = 2.22 g, DI = 2.00 g). This difference, however, was exacerbated when both treatments were inoculated with the root disease *pythium*. It was found that the DW system had suffered less yield loss, increasing the gap to around 20 %. Conversely, however, the DI system produced lettuce with lower nitrates, a known carcinogen (Chazelas et al., 2022), as well as a greater density of phenolics and flavonoids, which are associated with nutritional value and flavour (Yao et al., 2004). Further research should seek to identify the impacts system types have upon the quantity and quality of yields. Additionally, optimization of crop/sub-system combinations in conventional systems should extend towards identifying optimal crop/sub-system/organic fertiliser combinations.

The initial consideration when applying a nutrient solution is the rate of application. Ultimately, this determines both the concentration of the solution, as well as manages fluctuations in salinity, pH, and nutrient availability for the plant throughout its growth stages. The method for application can be broken down into *Temporal* and *Conditional* factors. *Temporal* considerations include the "when" of application : i*)* Once at the beginning of the growth period, *ii)* at *x* time interval, iii) at *x* EC, iv) at *x* nutritional density. *Conditional* considerations ask "how much" solution is required, including : i*)* To *x* EC, *ii)* to *x* nutritional density, *iii)* to *x*% of total volume, iv) *x* (volume.

There is no strong link between temporal factors and the success of trials. Trials which dosed to the required nitrogen had a higher rate of success relative to other methods (Kechasov et al., 2021; Tikasz et al., 2019). Papers which dosed based "*to x EC"* generally selected to meet the recommended EC of conventional solutions (Wang et al., 2019; Sunaryo et al., 2018; Abd-Elmoniem et al., 2001). The most representative technique, however, was to dose at fixed dilution rates without further explanation in methodology (Nanik and Muslikan, 2021; Liedl et al., 2006; Guntara et al., 2021). Future research should strive to specify both temporal and conditional factors when noting methodology.

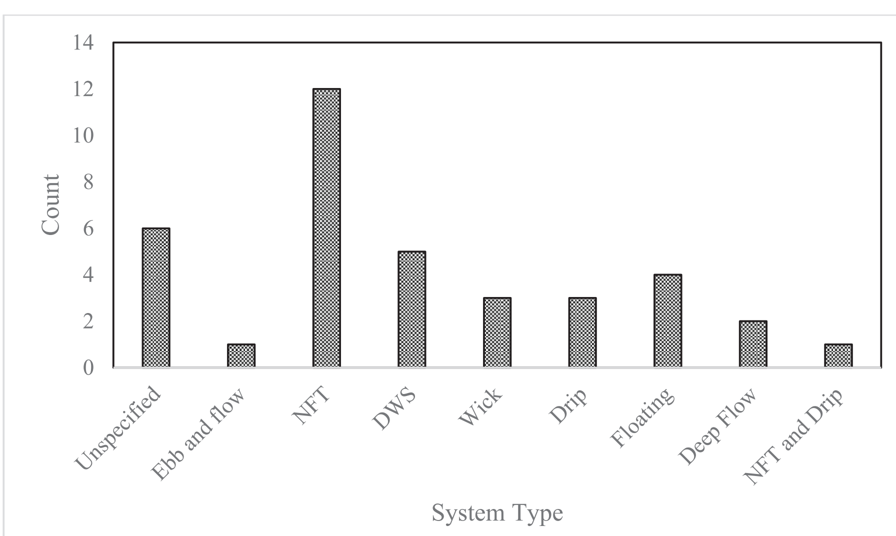

Fig. 4. Distribution of hydroponic system types across reviewed literature (n = 37).

3.7. Microbial activity

Within this review, there are two distinct areas of discussion surrounding microbial activity in the development and application of organic hydroponic solutions. Firstly, there is the role of microbes during the development of fertilisers, and the second being the role of microbes during cultivation. Despite having different contexts, the two areas share historical similarities regarding the conventional expectations of what an *ideal* hydroponic system should contain – that being, as little microbial activity as possible. The original development of hydroponics sought to develop a method for growing plants in a ceteris paribus scenario, with the goal of eliminating unpredictable microorganism behaviour – culminating in a culture of sterilisation (Garland, 1994). Similarly, standard conventional hydroponic solutions were comprised of synthetic, minerally sourced nutrients – sterile by nature. This was to assist in understanding the exact nutrients required by plants during their growth and offered scientists a stronger understanding of the key macro- and micro-nutrients required for optimising plant growth across the agricultural industry. Encouraging microbial activity during cultivating challenges the dogma of a sterile growing environment. Extensive research has been undertaken to understand, and subsequently minimise the presence of microbial communities within systems. However, there is potential to apply existing understanding of micro-community interactions to develop a balanced ecosystem within growing systems. While no paper compared an inoculated with a non-inoculated organic solution, papers such as Kechasov et al. (2021) created synthetic treatments with an identical nutritional composition of the organic solution. A comparison of the treatment and its synthetic clone found that there were less trusses, but greater fruit weight in the organic solution. This could be attributed to the availability of available nitrogen in early stages of plant growth but may also indicate another factor augmenting the performance of the solution.

3.7.1. Primary functions of microbes

The essence of microbial behaviour is the colonisation and growth of populations in nutrient rich biomes. How these populations interact with the surrounding environment then dictates whether a species is considered beneficial or harmful. This is the case in both the development of organic solutions and during operation of hydroponic systems.

3.7.1.1. The role of microbes in the development of hydroponic solutions. Microbes played a role in developing FWBHF's in 32 of 37 reviewed papers. The most replicated method was fermentation or digestion ($n = 22$). This process relies on microbial actors to remineralise organic material into plant-available inorganic nutrients. An unmanaged fermentation will naturally develop, and host microbial communities based on the environment and available sources of nutrients. This spontaneous community will break down organic matter into a variety of forms over time. While spontaneous, the microbial communities which establish and populate a fermentation can be influenced by manipulating environmental factors such as temperature, aeration, and inputs. Using these tools, researchers can optimise the repeatability, nutritional content, and quality of a solution through the cultivation of ideal microbial populations. Temperature can be adjusted to favour certain species; particularly as different stages of breakdown occur. Alterations in temperature can affect the speed of digestion, as warmer environments increase microbial activity, and thus accelerate stages which rely upon microbial agents (Youcai and Ran, 2021). Additionally, certain temperature ranges can favour particular microbial biomes – such as increasing temperatures up to 60 °C to kill parasite eggs effectively in anaerobic fermentations (Youcai and Ran, 2021). Similarly, the rate of aeration influences the speed of nutrient breakdown, such as increasing rates of mineralisation of ammonia. In addition, aeration can also be used to increase pH through the removal of CO2, or prevent the development of unwanted anaerobic species (Colt and Kroeger, 2013a, 2013b; Thauer, 1998). An example of application could be to lower temperatures and begin aeration of an anaerobic solution as it begins methanogenesis. The combination of increasing available oxygen and cooling the solution prevents the development of methanogens, and pivots NH3 breakdown away from CH4 and towards solubilised NO3 – a plant available nutrient.

Alteration of a FWBHF through inputs can be distinguished into "primary feedstock" and "additives". Primary feedstock includes the bulk of the nutrient source, while additives cause change through chemical, physical, or biological influences. Primary materials include the bulk of organic matter which is to be broken down into the organic solution. Ideal primary inputs will also include a balanced composition of NPK rich matter coupled with carbon-based nutrients to supplement microbial populations. Additionally, primary inputs may be pre-processed – converted from food-waste into a primary input by a number of physical alterations, including heating, mashing, chopping, crushing, or otherwise alter its physical form to improve surface area and microbial accessibility. Chemical additives can include pH manipulation, which alter nutrient availability and microbial communities, or include enzymatic agents such as proteases which may accelerate the breakdown of feedstock. Physical additives include increasing available surface areas for microbial colonisation. This generally consists of inert, porous material such as volcanic rocks, filter media, or sponges. By improving the population and stability of the microbial environment, the rate of fermentation increases. Biological additives are generally the direct inoculation of preferred microbial species. By exploiting the closed system of fertiliser development, a microbiome can be inoculated and managed to cultivate a preferred microbial species - leading to potential improvements in replicability, nutrient availability, and/or time of production.

3.7.1.2. The role of microbes during cultivation of plants. In growing systems, tradition dictates a sterile environment. However, upon reviewing historical literature, this philosophy was known to be misguided as far back as 1994. Still, the development into the eradication of microbial communities continued, with multiple commercially available of chemical additives designed to purge hydroponic systems of microbial communities. An example of a beneficial community is the naturally occurring population around crop rhizospheres. These populations are dedicated to the decomposition of dead tissue and root secretions, improving resilience to disease and improving nutrient uptake capacities (Porter, 1994). Recent research has provided a more intentional and active role for microbes, with Lind et al. (2021) utilising an aerated nitrification reactor which actively converted ammonia into nitrates during the growing cycle.

Such beneficial microbes found within hydroponic systems have been identified as "plant growth promoting microorganisms" (PGPMs) (Sheridan et al., 2017). Such organisms have been greatly studied in recent years, with variants of traditional soil-based PGPMs, such as *Arbuscular mycorrhiza* fungi and *Rhizobium* species (Dhawi F., 2023). The identification of beneficial strains can enable growers to adjust environmental conditions to cultivate these species to improve yield outcomes and reduce use of pesticides, algaecides, and synthetic fertilisers.

A final consideration is how biologically active a FWBHF is when it is ready for use in a hydroponic system. A sterilised solution presents itself as a vulnerable environment for any microbial population to exploit – wanted or not. Options to continually sterilise a solution without disturbing root biomes include UV sterilisation. However, a study into the efficacy of UV sterilisation as a preventative to *Pythium* found that while there were short-term benefits, eventually a population would establish itself in the rhizosphere of plant roots anyway – especially as non-target bacterial species start to decline as a result of irradiation (Zhang et al., 2020). An alternative, that has been, and is continued to be explored is inoculation of beneficial or benign bacteria that can prevent plant diseases from establishing impactful populations. The introduction of

Bacillus cereus into hydroponic systems was shown to lower the rate of *Pythium* root rot occuring by up to 20 % (Lee and Lee, 2015). Additional research utilised *Streptomyces griseoviridis* as an alternative to physical and chemical methods to successfully control *fusarium* wilt (Lee and Lee, 2015).

3.7.2. Inoculation and cultivation of microorganisms

Overall, this review concludes that there was no strong evidence for inoculation or supplementation of soluble carbohydrates as determining factors for the success of a food-waste based solution.

The direct inoculation of microbial strains was only mentioned in 10 of the 37 research papers. Four of these papers were digestate based, one was powder based and the last was raw. None of the strains were specified by species or name. It is difficult to prove a correlation between the inoculation of microbes and an altered outcome in the resulting yield of a trial. In future studies it may be worth comparing the effects of deliberate inoculation with otherwise identical inputs, systems, and crop species.

Similarly, the effects of simple carbohydrate additives were not convincingly successful or unsuccessful. The encouragement and facilitation of microbes did not play a pivotal role in the performance of a solution. Across the solutions, nine utilised simplified carbohydrates, most frequently sugars of white sugar, brown sugar, and molasses.

3.7.2.1. Inoculation. Inoculation involves the deliberate introduction of a specific or group of micro-organisms into a solution. Through inoculation the micro-community of a solution can be customised to perform specific functions. These functions can range from establishing a community that can optimise breakdown, prevent disease, and enhance rhizosphere activity in plant root systems. For example, when digesting meat, the protected environment of a digestor limits processing agents to microbial activity. Without naturally occurring arthropods and vertebrates, microbes are limited in their ability to penetrate tissue material. While physical barriers can be broken with physical processing techniques, microscopic elements such as cellulose, lignin, and proteins still require chemical or biological breakdown. A potential solution may be the introduction of specialised microbes, such as proteolytic bacteria can be introduced to produce protease enzymes and accelerate the breakdown process of the inputs. This can be further optimised to include multi-stage inoculations depending on the breakdown stage of the input. Xu et al. (2022), performed a multi-stage inoculation utilising different bacteria species on composted food-waste and found that this process expedited the rise in temperature and extended the thermophilic period from four to seven days – expressing a prolonged period of elevated microbial activity. Additionally, the resulting digestate had a more complete mineralisation, with only 10 % of the initial $NH4+$ content remaining after the trial period – with neither the control nor one-stage inoculation being able to reduce the $NH4+$ content beneath 33 % in the same time period.

Methodology with details of inoculation were limited, although several stand out as promising avenues for future research. Figueroa et al. (2015) exposes an anchovy wastewater-based solution to an autoclaving process prior to fermentation. Sterilisation of a treatment solution prior to fermentation is a unique method in this review. Researchers can inoculate their nutrient rich solution with specific strains of bacteria, such as *Bacillus* that are optimal for the breakdown of their specific inputs. Whether or not this additional step impacts the outputs is unknown, as a non-sterilised treatment group was not present. Future research exploring the impacts of sterilisation may enable more reliable inoculation stages – particularly exploring whether sterilisation pre- or post- fermentation is more effective in managing a productive growing system.

Within the scope of this report, no paper reported specific inoculant species. 10 papers reported deliberate inoculation during the development of their solutions. Eight of these were digestates. This area of research is generally underreported. Future research should strive to identify, as best as possible, the selected strains of inoculants, as well as time of inoculation and conditions of the system.

3.7.2.2. Cultivation of bacteria. Whether inoculated or not, a microbiome can be encouraged to grow through the addition of soluble carbohydrates such as sugar or molasses. This provides, in theory, several benefits regarding the longevity, expansion, and efficacy of microbial colonies. The presence of sugar provides a fast source of energy for colonies to expand and establish quickly in a solution (Lievens et al., 2015), it also allows microbes in solutions with primary inputs composed of fibrous vegetation with complex polysaccharides – such as bamboo or sugar cane stalks– to have a source of nutrients while the material is slowly broken down. Only 8 papers reported additives directed for microbial consumption. *Phibbunwatthanawong* et al. (2018) measured the effects of a fermentation with and without sugar. Utilising ethanol slop, sugarcane leaves, and molasses in differing ratios, fermentations were anaerobically fermented for 30 days.

Nutrient analysis was performed once at 15 days, and again at 30 days. Day 15 found that the F4 solution had the highest nitrogen and potssium content. However, by day 30, F6 had a superior nitrogen and potassium content. Despite this, in the ensuing growth trial, the lettuce (*lactuca sativa)* yielded the greatest fresh weight was F3, matching the synthetic control in terms of fresh and dry weigh. A comparison between F3 and F2 shows that the source of carbohydrate may play a role in the conversion of food-waste into a functioning nutrient solution. Molasses represents a relatively simple carbohydrate which does not require a diverse microbial community to break down, while sugarcane leaves require more specialised microbes which are capable of processing cellulose, lignin, and other structural materials. F3 may cultivate a more diverse community, providing greater opportunities for optimal spontaneous fermentation to occur. This highlights a gap in knowledge regarding the selection of supplements for microbes. Further research into the efficacy of long- and short-term sources of carbohydrates, as well as the resulting microbial communities may be key in identifying microbial species worth inoculating in future methods.

Current literature does not explicitly explore the role of sugars in food-waste derived hydroponic solutions. However, literature from fields in microbiology specialising in waste breakdown have identified the potential drawbacks of soluble carbohydrate additives. As shown in F2 of *Phibbunwatthanawong's* research, additions of sugar may hinder the development of a balanced biome. Additions of sugar should be carefully considered – especially in solutions where the primary inputs are rich in proteins. In the decomposition of meat, proteolytic bacteria play an essential role in the breakdown of protein. However, proteolytic bacteria have a relatively slower growth rate compared to bacteria that rely solely on carbohydrates to grow (Kieliszek et al., 2021). Thus, when adding sugar, the amount added should be calculated such that it provides adequate energy to the relevant microbial communities without excess sugars. Excessive sugar can lead to the growth of unwanted microbes and impede the development of microbes better optimised for the breakdown of proteins and other more resilient carbohydrate sources (Horváth et al., 2020).

Remaining literature probes at the potential effects of carbohydrate supplements in hydroponic systems. Kano et al. (2021) uses corn steep liquor (CSL) as an additive to develop a rhizosphere community. With the goal of cultivating bacteria capable of mineralising organic nitrogen, it was found that when used alongside a commercial organic solution, the fresh weight of lettuce was able to meet the efficacy of the synthetic control if given an extra week prior to harvest. While there was no specific study into the impacts of the CSL itself, this research continues exploration into the idea of a biologically active hydroponic system. Future studies should explore the dynamics of supplements and microbial communities in hydroponic systems during cultivation (Table 13).

Table 13
Ratio of ethanol slop, sugarcane leaves, molasses, and filtered water (volume, weight, volume, volume) utilised in Phibunwatthanawong et al. (2018).

Treatment	Ethanol slop	Sugarcane leaves	Molasses	Filtered water
F1	1	0	0	0.25
F2	1	0	0.1	0.25
F3	1	0.1	0	0.25
F4	1	0.1	0.1	0.25
F5	1	0.25	0	0.25
F6	1	0.25	0.1	0.25

3.8. Gaps in knowledge and future recommendations

This section is organised in order of the discussion, identifying key gaps, and recommending potential avenues in feedstock, methodology, and microbial activity, for future research. Additionally, recommendations in reporting standards are also included.

3.8.1. Feedstock

Feedstock in the context of this review has a strong focus on the development of a functioning solution, however consideration towards differences in feedstocks based on consumer behaviour may also play a key role in organising future research. While largely auxiliary to the primary focus of this report, regional variations in food waste arise from socio-economic, cultural, and geographic differences. For example, households with increased income tend to consume – and waste – proportionally greater amounts of fresh produce and proteins compared to carbohydrates (Ishangulyyev et al., 2019; Lopez Barrera and Hertel, 2021). An example of cultural preference influencing food waste is a vegetarian population producing food-waste with a lower average protein content compared to a more carnivorous population (Sibal, 2018). Finally, the geography of a region influences what is readily available, such as rice in warm, wet climates compared to wheat in drier, cooler climates (Sharma et al., 2022). All these factors may influence the composition of a feedstock, which in turn may impact the effectiveness of particular methods and the nutrient composition of a final product. This review identified nine papers which utilised waste generated from consumer or retail levels, only two papers provided complete profiles of the feedstock (Giménez et al., 2020; Yusuf et al., 2021). The remaining seven papers identified food waste as "café/kitchen/industrial kitchen-waste". Improved reporting and research exploring regional variations in food-waste clarifies directions for future research by organising processing methods based on feedstock similarity – ultimately optimising processing methods for local food-waste sources. Finally, the functional requirements of a FWBHF vary regionally. Consumer preferences determine whether a FWBHF is of sufficient efficacy. Simply, if a population demands fresh strawberries, the FWBHF must satisfy the nutritional requirements to yield profitable amounts of strawberries. Understanding regional food-waste availability and produce preferences familiarises researchers with their feedstocks and the desired nutritional outcomes they must meet.

Quantifying how feedstock interacts with processing methods is the backbone of refining FWBHF research. Interactions can be primarily quantified by yield outcomes, although assessing nutrient content, food-safety risks, and disease resilience may also prove useful. Along with this, unique interactions with food-waste should also be explored – some waste may have properties which can alter the solubility or microbial composition of a solution, such as Sawain et al. (2020) using of powdered crab shell as a natural flocculant, or Kano et al. (2021) utilising corn steep liquor to enhance existing synthetic or FWBHF solutions.

Overall, this review has identified the importance of adjusting methodology to accommodate for available food waste. Future research should focus on managing existing sources of urban, consumer level food waste. This can be achieved through both specialist and broad approaches. A specialist approach should strive to assess the nutritional, microbial, and chemical changes in specific foods under specific conditions. A broad approach better captures the inevitable variance of food-waste, including shifts in competing microbial populations, changes in pH, or nutritional fluctuations. An example of a specialist approach is the process of milling and powdering fish as a source of hydroponic nitrogen. Kawamura-Aoyama et al. (2014) implemented this specific methodology while measuring for a specific outcome (Available nitrogen) – providing an intimate understanding of how fish acts as a FWBHF after it has undergone a powdering process. Conversely, Siddiqui et al. (2021) utilises digestion with a large range of foods sourced from the restaurant industry. By providing a pilot study on the interaction between digestion and real food-waste, limitations such as excess sodium were able to be identified. Hence, both approaches are relevant in the study of FWBHF development. With the current level of research, both hold great potential in furthering development of FWBHF's.

3.8.2. Methodology

Processing methodologies are the focus of research in FWBHF development. Existing research covers range of trialled methodologies under a myriad of conditions, producing a largely fragmented patchwork of knowledge. The currently most understood processing method is fermentation, due to both its prominence in FWBHF as well as its relevance in other disciplines. Despite this, there is little evidence in the reviewed literature to suggest that fermentation, either aerobic or anaerobic, is better than other methods. The lack of consistent feedstocks, system types, substrates, lighting conditions, and crops across papers limits the identification of common trends of success.

Fermentation, however, highlights the importance of effective and clear reporting. Existing research of fermentation techniques included examining yield efficacy, nutritional content, and length of fermentation (Siddiqui et al., 2021; Phibunwatthanawong and Riddech, 2019). The chemical changes because of both anaerobic and aerobic fermentation are well documented – methanogenesis, nitrogen mineralisation, and acidification are well studied pathways endemic to fermentation. This provides a clearer research direction for other methodologies – to develop a similar level of chemical, mechanical and functional understanding of the changes food-waste experiences under their respective conditions.

Many of the methodologies in this review can be considered novel and/or unique. After individual assessments of each method, the overall gaps in knowledge can be summarized as follows:

1) How processing methods impact organic matter breakdown chemically, microbially, and physically.
2) How microbial populations interact with particular processing methods with respect to processing time, nutrient availability, and safety of usage.
3) How different environmental and physical factors affect processing method efficacy.
4) How energy-efficient, scalable, and flexible a processing method is.

These conditions may also include alterations in substrates, optimal lengths of processing, microbial inoculations/facilitation, subsystem-specific interactions, active integration into subsystems, and the impacts made by feedstock content. Alongside existing studies, future research recommendations include exploring heavy metal analysis, food-safety studies, plant disease impacts, microbial content analysis, and optimal system types. An example of future research could explore boiling and steaming as a method for FWBHF production. While the effects of boiling and steaming on nutrients for human health are well understood, there is limited information regarding plant-relevant nutrients as a result of boiling or steaming food-waste (Lee et al., 2018a, 2018b; Yong et al., 2019). Future studies into these processes could explore plant-nutrient availability differences between a 15-min blanch and a 3-day hard boil of vegetative waste. Although research into these two methods should also consider energy costs, and its scalability to industrial levels.

Similar to fermentation, research into vermiliquer benefits from a multidisciplinary presence. While this review was not able to claim that an unmodified vermiliquer is an adequate FWBHF, on-field trials have provided evidence for improved long-term yields, increased microbial activity, and potential to remove heavy metals and pathogens from substrates (Churilova and Midmore, 2019; Singh et al., 2011). Within this review, only the effects of raw vermiliquer have been documented, future research should explore whether post-processing techniques such as fermentation may impact the efficacy of a vermiliquer FWBHF.

A fermented vermiliquer posits the potential of synergy between processing methods in FWBHF development. The impacts of synergistic, or multi-stage processing on FWBHF's are largely understudied. Examples of multi-stage processing can be observed in papers which utilise biogas digestate. Generally, additional processing includes additional anaerobic fermentation of biogas followed by supernatant extraction (Ronga et al., 2019; Lind et al., 2021; Ntinas et al., 2021). A deviating methodology included adding biogas digestate into an operating hydroponic system with active aeration to facilitate the mineralisation of ammonia into plant available nitrates. Another example is the drying, and powdering of feedstock (Kawamura-Aoyama et al., 2014; Sawain et al., 2020). Further research could explore the benefits of each method, such as utilising vermiculture to homogenise food-waste into a liquid prior to bioconversion through fermentation processes. Alternatively, autoclaving may improve inoculation and cultivation of ideal microbial communities in a solution. The primary limitation of utilising multi-stage processing are the costs associated with additional processing stages, by extending processing times, required space, and labour. Hence, cost-benefit should be an eventual consideration when exploring multi-stage processing techniques.

A largely unmentioned synergistic process is the intentional, mechanical breakdown of feedstock, which is only mentioned in three of the nine consumer level research papers (Hilman et al., 2021; Kawamura-Aoyama et al., 2014; Siddiqui et al., 2021). These processes can include grinding, milling, chopping, crushing, and mincing. The effects of prior mechanical processing have an unmeasured impact on the quality of FWBHF's, with none of the literature in this review performing a comparative process between mechanically processed feedstock and whole feedstock. There is a strong case for the exploration of utilising artificial mastication, which include improvements in microbial diversity, rate of breakdown, and plant-pathogen reduction (Mishra et al., 2018; Liu et al., 2022). Uniquely, it is the only process in this review that is exclusively used in conjunction with another method, likely due to its inability to incite large chemical changes in feedstock. The benefits largely derive from the breakdown of particles, mixing of materials, and homogenising of feedstock. For example, Liu et al. (2022) found that using fine bonemeal instead of whole bones in a cellulose rich compost reduced the presence of pathogens such as *Phaeoacremonium*, *Acremonium*, and *Geosmithia* as well as increasing the final TN content. Hence, future research may choose to explore the effects pre-processing feedstock by masticating and mixing feedstock have on the outputs of other methods.

Future research could focus on optimising hydroponic systems by adapting to the unique properties of FWBHF. This optimisation may include adjustments in solution temperature, system type, lighting, and irrigation scheduling. Practically, it is preferable to modify fertiliser development to fit established hydroponic systems, such as NFT or floating raft systems, incorporating small modifications such as mesh traps, porous substrates, and bioreactors as methods to manage debris, support microbial communities, and improve nutrient conversion during the growth period. A notable innovation could be the integration of active nitrifiers, similar to those used in aquaponics. This approach replaces fish waste with processed food-waste as a source of nitrogen, potentially improving the longevity of existing plant-available sources of nitrogen for FWBHF use.

Salinity and sodicity are a major obstacle in the development of effective FWBHF's. The imbalance between EC (electrical conductivity) and plant available nutrients is observed across majority of papers. Current research into the management of salinity and sodicity in FWBHF's is limited. Existing desalination projects include the conversion of from sea- or saline ground-water into potable water, as well as the neutralisation of sewerage waste (Khawaji et al., 2008). These systems tend to be industrially sized, and have high initial and ongoing costs associated with their operation – requiring industry level effort of food-waste management. New research into ion sieves for desalination may prove to be a future solution, however this solution is far from commercial application. Whether any processing methodology impacts salinity is largely unknown. Future research could entail methods of lowering EC relative to other nutrient levels, although cost effective methods to do so are somewhat limited.

3.8.3. Microbial activity

Applications of microbial actors in FWBHF's is an understudied area of research. While new papers are common, the range of available future research far exceeds existing literature. Beginning with managing existing microbial populations, considerations for future research include optimal temperatures, aeration, substrate selection, and chemical additives to optimise cultures for plant production. The extension of this research is to explore potential species for inoculation – these populations may have the potential to improve yield, prevent disease, as well as stabilise nutrients (Dhawi, 2023). Continued optimisation can include identifying optimal inoculation timing, interactions with different food groups, as well as whether if inoculated species should be removed prior to use in an operating hydroponics system.

3.8.4. Standardized reporting

While in its infancy, the development of food-waste into organic hydroponic systems is quickly gaining momentum as a topic of research. The opportunity to re-utilise food waste as a method of securing local fresh produce in a sustainable manner has greatly increased interest in this research area. Currently, independent investigations are probing potential techniques for processing a plethora of food-waste sources. In lieu of this, it would be prudent to begin developing a standardized reporting system. Table 14 lists a range of elements found to be relevant that should be included across FWBHF research. These factors are chosen and ranked into three priorities*: high, medium*, and *low*.

- *High* priority reporting elements have been selected as essential components of research which are relevant across all disciplines within FWBHF research. They have been selected due to relevance as well as being easy to measure and report.
- *Medium* priority reporting elements may have more specific areas of research or are limited by costly or time intensive methods of data collection.
- *Low* priority reporting elements tend to be niche and difficult to collect. This information is largely delegated to the study of specific interactions and should be included if available and relevant.

4. Conclusion

Continued development into FWBHF will benefit both food-waste management and food production systems in urban environments. This development assists in the transition of a linear flow of nutrients towards a cyclical structure, reframing “disposal” of food-waste as “leakage,” ultimately normalizing notions of recycling food-waste. By introducing a stigma against disposing of food-waste, future infrastructure can accordingly accommodate to sort, process, and utilise the waste generated by urban populations.

Table 14
This table can be used as a reference guide for key variables for future research in FWBHF development.

Stage	Priority	Reporting element	Description	Example
Inputs	High	Primary inputs	A % mass/volume breakdown or total mass/volume measurement of the feedstock.	Household waste (20 % meat and bones, 40 % veg scraps, 40 % eggshells)
	High	Physical additives	Any materials which are added to alter the physical environment to prevent settling, host microbes, or manage pH	Lava rock, bio-balls, stirrers, etc.
	High	Chemical additives	Any supplements which affect the chemical attributes of a solution	pH buffers, antiseptics, nutrient supplements
	High	Biological supplements	Any inoculations or intentional introduction of materials which aim to alter microorganism activity.	Microbial strains, sugars
Techniques	High	Pre-processing	Methods which do not cause significant chemical change to the feedstock.	Mash, chop, crush
	High	Processing method	The primary processing method/s utilised	Fermentation, vermiliquer
	High	Processing time	A time measurement of any processes that feedstock has undergone.	30 day fermentation, 21 day steam
	High	Solution temperature	The temperature of the solution during processing	Fermentation managed at 30 °C
	High	Aeration	Include specific details such as method, flow rate, and operational hours	Stirred for 30 s twice a day, aerated at 320 L/h
Analysis	High	EC	A measurement of the undiluted solution	EC = 4.5 dS/cm
	High	pH	A measurement of the undiluted solution	pH = 4.5
	High/ medium	NPK	An analysis of key macronutrients	N = 1090 μg/L P = 230 μg/L K = 1560 μg/L
	Medium	S, Ca, Mg	An analysis of key macronutrients	As above
	Medium	Micronutrients	Nutrient analysis of assorted micronutrients	As above
	Low	Microbial analysis	Methodologies used which identify microbial populations	S16 extraction
During Operation	High	System type	The type of subsystem used	NFT, DWS, DS
	High	Frequency of irrigation	If NFT system, include flow rate and volume of reservoir. For DWS include frequency of flooding and duration.	(NFT) Flow rate of 200 L/h w/ 400 L reservoir. (DWS) Flooded every 6 h for 2 min.
	High	Crop species	The crop species, including scientific name and variety	Lettuce (*Lactuca sativa)*
	High	Substrate used	The type of substrate the crop is planted in	Rockwool, Cocopeat
	High	Frequency of FWBHF application	Application rate of fertiliser, including dilution rates, timings, or goal pH/EC/NPK levels	Dosed to EC of 1.6 dS/cm Dosed to TN = 200μg/ml
	High	Ambient conditions	Hours of lighting, air temperature, humidity and the presence of ventilation or CO2 supplementation	16 h of light a day at ~30 °C with 65 % humidity.

The existing landscape of FWBHF research presents a variety of novel approaches with varying degrees of success. Reviewed literature is largely exploratory, trialing different methodologies with a range of feedstocks. Future research should strive to isolate individual agents which facilitate the greatest change. Whether it be processing methods, feedstock additives, growth system modifications, or microbial inoculations, the continued improvement of existing methods, or the discovery of new methods is critical to building towards developing effective food-waste management techniques as well as a sustainable foundation for urban horticulture.

CRediT authorship contribution statement

Oscar Wang: Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Rosalind Deaker:** Writing – review & editing, Supervision, Conceptualization. **Floris Van Ogtrop:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

None.

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Data availability

Data will be made available on request.

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