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Integrated hydroponics systems with anaerobic supernatant and aquaculture effluent in desert regions: Nutrient recovery and benefit analysis

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Highlights

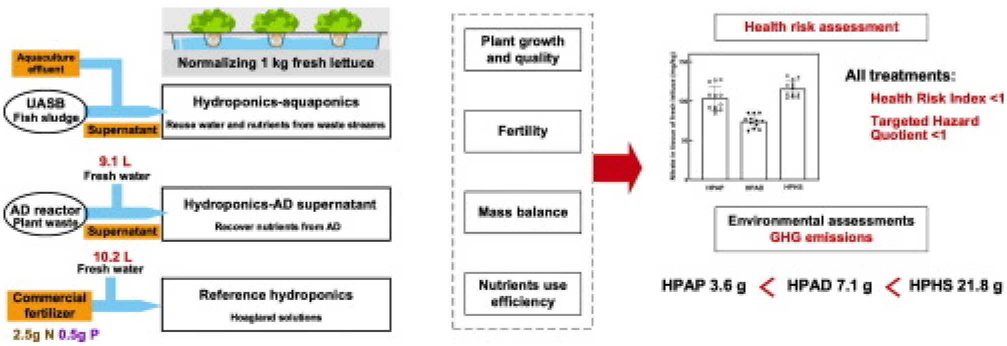
- Reuse of waste streams as nutrient sources for hydroponics in arid zones
- Uptake rates of 77%N and 65% P from anaerobic supernatant and aquaculture effluent
- Large water saving (10L per kg of lettuce) and enhanced plant growth and quality
- Negligible health-risk index with low heavy metal and nitrate accumulations

- Studied hydroponics reduce pollution and GHG emissions, and improve sustainability.

Abstract

Hydroponics is a resource-efficient system that increases food production and enhances the overall sustainability of agricultural systems, particularly in arid zones with prevalent water scarcity and limited areas of arable land. This study investigated zero-waste hydroponics systems fed by agricultural waste streams as nutrient sources under desert conditions. Three pilot-scale systems were tested and compared. The first hydroponics system ("HPAP") received its nutrient source internally from an aquaponic system, including supernatant from the anaerobic digestion of fish sludge. The second system ("HPAD") was sourced by the supernatant of plant waste anaerobic digestion, and the third served as a control that was fed by commercial Hoagland solution ("HPHS"). Fresh weight production was similar in all treatments, ranging from 488 to 539 g per shoot, corresponding to 5.7 to 6.0 kg total wet weight per m^2. The recovery of N and P from wastes and their subsequent uptake by plants was highly efficient, with rates of 77% for N and 65% for P. Plants that were fed using supernatants demonstrated slightly higher plant quality compared with those grown in Hoagland solution. Over the duration of the full study (3 months), water was only used to compensate for evapotranspiration, corresponding to ~10 L per kg of lettuce. The potential health risk for heavy metals was negligible, as assessed using the health-risk index (HRI < 1) and targeted hazardous quotient (THQ < 1). The results of this study demonstrate that careful management can significantly reduce pollution, increase the recovery of nutrients and water, and improve hydroponics production.

Graphical abstract



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Introduction

Supporting food security in light of growing populations, climate change, and land degradation is one of the most significant global challenges (FAO, 2022). Arid zones already cover >40% of Earth's land surface and host over 40% of the global population, and processes of desertification followed by land degradation further exacerbating environmental quality and food production in these zones (Froehlich et al., 2018). Addressing these problems and challenges has stimulated the design of adequate and sustainable food systems for drylands that maximize water- and nutrient-use efficiency. Soil-less production systems (also known as hydroponics systems) may be advantageous where water and nutrient-rich arable lands are scarce (Resh, 2016). Moreover, reducing the dependency of hydroponics on chemical fertilizers would also increase the sustainability of these systems (Schmautz et al., 2022). One option in this respect is to utilize agricultural-based waste and nutrient-rich effluents to replace the use of chemical fertilizers (Yogev et al., 2020).

In hydroponic systems, plants are grown in soil-less, controlled settings, enabling year-round cultivation, especially in regions with space constraints like urban or arid zones (Resh, 2016). Research has demonstrated that hydroponic systems facilitate faster growth rates of 30% to even 500% compared to traditional farming, yielding higher productivity and reduced fertilizer use (Goddek et al., 2019; Groenveld et al., 2019). Furthermore, hydroponics may reduce land and water requirements by 75% and 90%, respectively, presenting a potential solution to global food scarcity (FAO et al., 2021). While it was stagnant for many years, the agricultural application of hydroponics between 2011 and 2020 increased by about 60%, elevating its production value three folds to 3×10^4 million US dollars, and this trend is expected to double by 2030, with leading contributors being nations like the US, Canada, China, and Brazil (Magwaza et al., 2020; Rockström et al., 2020).

Hydroponics food production generates a vast amount of agricultural waste, including solid waste and wastewater. This waste stream contains high-potential nutrients that may need to be mineralized before recycling (Junge et al., 2017). Agricultural organic solid waste, such as plant wastes, spoiled fruit, and sludge, has been estimated at >10 billion tons of annual biomass in arid regions (Molotoks et al., 2021). Another potential water and nutrient-rich source is aquaculture sludge, which has been estimated at 123 km^3 annually (FAO, 2022; Timmons et al., 2018). These wastes and sludges are generally considered an environmental and economic burden (Zhu et al., 2021).

The overall objective of the present study was to test the feasibility of reusing anaerobically digested plant waste and aquaculture effluent, including fish sludge, as nutrient sources for hydroponics and to compare these treatments with Hoagland (chemical-based fertilizer) hydroponics as a control. Utilizing aquaculture effluent and anaerobic supernatant for crop irrigation can offer multiple environmental advantages, including a reduction in freshwater consumption, curtailment of waste discharge, mitigation of environmental contamination, and a decrease in fertilizer-associated costs (Wongkiew et al., 2021). The introduction of supernatant from anaerobic digestion (AD) of fish sludge to traditional aquaponics has been suggested and tested (Yogev et al., 2018). In addition, the potential application of anaerobically digested plant waste supernatant to support plant growth has also been demonstrated (Zhu et al., 2022a, Zhu et al., 2022b). However, to the best of our knowledge, the present study is the first to systematically compare these nutrient resources with chemically based nutrient solutions in a long-term pilot hydroponics under desert conditions.

The potential presence of heavy metals and emerging organic pollutants in reused aquaculture effluent and anaerobic supernatant raises significant concerns regarding human health risks (Lee et al., 2021). Similarly, the accumulation of excessive nitrate and nitrite over time might lead to nitrogen toxicity, which, for example, affects young lettuce plants and harms human health (Pérez-Urrestarazu et al., 2019). However, although AD and aquaculture effluents contain micro- and macro-nutrients, adding fertilizer supplements such as iron may still be necessary to sustain plant growth (Schmautz et al., 2021). Therefore, analysis of the nutrient composition of crops and the heavy metals accumulated in them is essential to evaluate the health risk for determining agricultural recovery effluent as a nutrient solution for hydroponics.

Given the above background, the specific objectives of this study were to (1) compare the extent of plant growth in different hydroponics systems; (2) quantify the nutrient balances with different AD effluents (aquaponic waste or plant waste) used as fertilizers; and (3) evaluate potential health risks associated with plant consumption.

Section snippets

Hydroponics systems and experimental design

This study compared the performance of three hydroponics systems (HPs; Fig. 1). The tested systems are detailed in 2.1.1 Aquaponics-based hydroponics system (HPAP), 2.1.2 Hydroponics system with anaerobic supernatant (HPAD), 2.1.3 Hydroponics with Hoagland solution (HPHS) below. In brief, the first system was supplied with aquacultural effluent within an aquaponic system (AP) and supernatant from anaerobic treatment of fish sludge in an upflow anaerobic sludge blanket (UASB) reactor and is…

Hydroponics system performance

The vegetative growth characteristics of the lettuce harvested during the experiments are presented in Table 1. Eight cycles of lettuce were harvested, each with a growth period of 30 days (Fig. 2a). The initial and harvested plant mean weights were 2 and 552 g, respectively, corresponding to a mean yield of 5.79±0.22 kg lettuce/m^2, without significant differences between treatments ($p>0.05$). Moreover, the overall yield was similar to those of commercial farms in Israel (Zaks et al., 2021)…

Conclusions

This study investigated near-zero-waste hydroponics systems in desert regions using experiments involving the production of lettuce under three treatment systems. The hydroponics cultivation of lettuce using supernatant derived from anaerobically digested aquaculture waste or plant waste exhibited superior performance compared with the control Hoagland solution hydroponics system. Specifically, the two hydroponics treatments enhanced crop yield, increased fresh biomass, and improved plant…

CRediT authorship contribution statement

Ze Zhu: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Resources; Validation; Visualization; Roles/Writing - original draft.

Uri Yogev: Conceptualization; Methodology; Supervision; Writing - review & editing.

Karel J Keesman: Supervision; Writing - review & editing.

Shimon Rachmilevitch: Methodology; Writing - review & editing.

Amit Gross: Conceptualization; Funding acquisition; Investigation; Project administration; Resources; Supervision; Writing - review & editing.…

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.…

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