Asian Journal of Agricultural and Horticultural Research

Volume 10, Issue 4, Page 261-280, 2023; Article no.AJAHR.103034
ISSN: 2581-4478

An In-depth Investigation of the Pertinent Challenges Inherent in Hydroponics, Aeroponics, Aquaponics, and the Efficacy of Bioponics-based Organic Solutions in Mitigating Them

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Authors' contributions

Both the authors designed, analysed, interpreted and prepared the manuscript.

Article Information

DOI:10.9734/AJAHR/2023/v10i4268

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/103034

Original Research Article

Received: 19/05/2023
Accepted: 24/07/2023
Published: 02/08/2023

ABSTRACT

This study looks at current issues with hydroponics, aeroponics, and aquaponics and explores if organic bioponics-based solutions are a viable alternative that is also sustainable. The study's findings emphasize the need of maintaining root health and nutrient delivery in aeroponic systems, monitoring water quality and striking a balance between the health of fish and plants in aquaponic systems, and maximizing resource utilization in both systems. The utilization of natural pest and disease management techniques and the sustainable use of resources are just two advantages of bioponics, according to comparative studies. The absence of organic food sources, inefficient insect control, and expensive upfront costs are cited as challenges. The development of various organic nutrient sources, optimisation of biological control agents, analysis of commercial feasibility and scalability, automation of processes, integration of technology, and environmental impact analysis are some future research objectives. This study demonstrates how bioponics may help progress

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environmentally friendly farming methods. By pursuing the suggested future research lines, scientists can further support organic farming methods, improve the effectiveness of food production, and lessen the influence of agriculture on the environment. By identifying low-cost organic material for Agri input development like that done in the year long trials done by VIRENXIA with IIT-Delhi, appropriate solutions for accelerating sustainable crop growth can be achieved. It also aims to create a virtuous cycle between society and an inclusive academic system, by providing knowledge and practices for emerging farmers and upgrading the capabilities of agriculture sectors, in responding to the development needs of rural India.

Keywords: Hydroponics; disease management techniques; aeroponics; aquaponics.

1. INTRODUCTION

The development of hydroponics, aeroponics, and aquaponics has significantly changed the agricultural industry. These novel cultivation methods have become viable substitutes for traditional soil-based farming, providing several benefits including effective resource utilisation, increased crop yields, and little environmental impact [1]. Hydroponics, aeroponics, and aquaponics all have advantages, but they also have a number of problems that must be solved before they can be widely used and successful. This study work intends to undertake a thorough examination of the current issues with various cultivation techniques, offering insightful information about their intricacies and effects.

2. RESEARCH OBJECTIVES

The primary objectives of this research paper are as follows:

- To identify and analyse the contemporary challenges in hydroponics, aeroponics, and aquaponics.
- To explore the potential of bioponics-based organic products in addressing the identified issues.
- To evaluate the efficacy of bioponics in enhancing nutrient diversity, facilitating natural disease and pest control, and promoting sustainable resource utilisation.
- To provide practical insights and recommendations for growers and practitioners in the field of advanced agricultural systems.

3. LITERATURE REVIEW

3.1 Present Issues in Hydroponics

Due to the need on nutrient solutions for plant development in hydroponics, nutrient management is a significant concern. For maximising crop output and quality, studies have shown how crucial it is to maintain ideal nutrient balance and availability. To prevent deficits or toxicities in hydroponic systems, Asao [2] emphasised the necessity of careful regulation of fertilizer concentrations. They said that deficiencies of vital minerals including calcium, magnesium, potassium, nitrogen, and phosphorus might have a detrimental effect on the growth and development of plants. In soilless situations, it can be extremely difficult to handle diseases and pests. The susceptibility of hydroponic plants to ailments brought on by pathogens including Pythium, Fusarium, and Phytophthora was explored by Sharma et al. in [3]. To reduce the danger of disease outbreaks, these authors emphasised the need of putting into practice suitable sanitation practices, such as disinfecting tools and substrates.

3.2 Present Issues in Aeroponics

As a cutting-edge growing technique, aeroponics has particular difficulties with nutrient delivery and root health. In order to minimise root dryness and encourage the best possible plant development in aeroponic systems, Kumari & Kumar [4] emphasised the crucial need of a sufficient and reliable moisture supply. To guarantee a constant flow of water droplets to the plant roots, the scientists emphasised the need of keeping exact control over the misting system. Another significant obstacle in aeroponics is the optimisation of root growth. The significance of creating aeroponic systems that provide the roots enough oxygen was covered by Cai et al. in 2023. They described how low oxygen levels might result in stunted root development and increased susceptibility to illnesses.

3.3 Present Issues in Aquaponics

Maintaining a balanced environment between fish and plant components is difficult with aquaponics, which combines aquaculture with

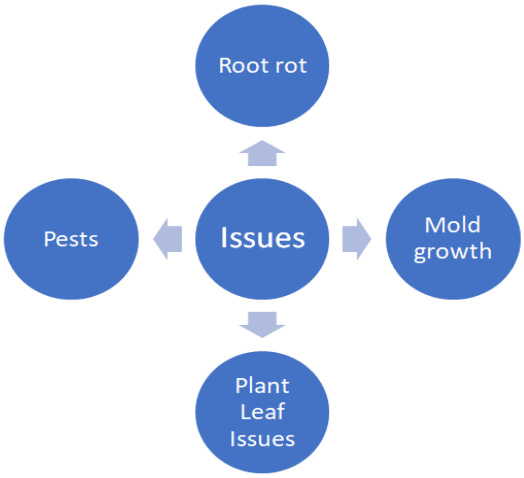

Fig. 1. Hydroponic Isuues

hydroponics. For optimal plant growth and fish health in aquaponic systems, Love et al. [5] emphasised the need of ensuring effective nutrient cycling. They talked on the difficulties in maintaining balanced nutrient ratios, particularly for nitrogen and phosphorus, to avoid nutrient shortages or excesses in both fish and plant parts. Managing water quality is a major difficulty in aquaponics. A healthy aquatic environment must be maintained by proper monitoring and regulation of factors including pH, dissolved oxygen, ammonia, nitrite, and nitrate [5]. Ineffective water quality management can result in stressed fish, poor plant development, and unbalanced nutrient availability.

3.4 Potential of Bioponics-Based Organic Solutions

A viable strategy to overcome the difficulties in hydroponics, aeroponics, and aquaponics is the integration of bioponics-based organic products. The advantages of employing organic inputs, such as compost teas, microbial inoculants, and biofertilizers, in soilless farming methods were examined by Rockström et al. [6]. These writers emphasised the function of advantageous microbes in boosting nutrient availability, encouraging plant development, and controlling plant diseases. Organic solutions based on bioponics also include the use of biological control agents (BCAs). BCAs, such as parasitoids, beneficial nematodes, and predatory insects, can control diseases and pests in soilless systems [6]. Using integrated pest control techniques that include BCAs has reduced pest populations and reduced the requirement for chemical pesticides, showing encouraging results.

4. METHODOLOGY

In order to achieve the research objectives, the methodology for this study takes a comprehensive approach that blends qualitative and quantitative methodologies. Semi-structured interviews with specialists in the fields of hydroponics, aeroponics, aquaponics, and bioponics will be used to gather the primary data. Traditional interviews will shed important light on the modern difficulties that traditional cultivation techniques face, as well as the effectiveness of organic bioponics-based solutions.

To choose people with in-depth knowledge and expertise in the subject, a purposive sampling approach will be used. To ensure that the participants can offer in-depth information regarding the difficulties they have faced and their viewpoints on potential solutions, the interviews will either be conducted in person or through virtual platforms. Some primary data and interviewed sources been kept away from the published realms of this paper, due to Patent and IP restrictions.

Secondary data will be gathered from a variety of academic sources, such as research publications, academic papers, and industry reports, to supplement the original data. These sources will be examined to learn more about the problems that hydroponics, aeroponics, and aquaponics are now facing as well as the promise of organic, bioponics-based solutions. The secondary data will be used to identify knowledge gaps and lay the groundwork for theoretical comprehension.

The main and secondary data gathered will go through a thorough analytical procedure. Interview-derived qualitative data will be transcribed and thematically analysed. We will identify and categorise recurring themes and patterns in relation to the difficulties in hydroponics, aeroponics, and aquaponics. The conclusions will be backed up with quotes and snippets from the interviews.

Relevant quantitative information will be acquired from secondary sources for the quantitative analysis, including statistics on crop yields, nutrient concentrations, and disease incidence. Descriptive statistics, correlation analysis, and regression analysis will be used to analyse this data in order to explore the connections between variables and spot any trends or patterns.

5. RESULT AND DISCUSSION

Relevant statistics, tables, and graphs will be used to support the discussion in order to convey the study findings in a clear and thorough manner. The research will address current difficulties in hydroponics, aeroponics, and aquaponics as well as the possibility of bioponics-based organic solutions. The findings will be organised based on the research objectives.

5.1 Present Issues in Hydroponics

5.1.1 Lack of nutrient diversity: Implications and mitigation strategies

Crop quality and production may be impacted by the lack of nutrient variety in conventional hydroponic systems. According to study findings, depending only on synthetic fertiliser solutions may result in shortages or imbalances in vital nutrients, which might impair plant growth and development. Hydroponic systems with organic fertiliser sources have showed potential in addressing this problem. Organic nutrition sources can increase nutrient variety and supply extra micronutrients and organic matter to boost plant development [7]. Examples of these sources include compost teas, organic fertilisers, and plant-based extracts. The comparison of nutrient content in synthetic and organic nutrient solutions is presented in the Table 1.

5.1.2 Disease and pest management: Analysing complexities and effective approaches

The research's findings show how difficult it is to manage disease and pests in hydroponic systems. Hydroponically grown plants are more vulnerable to illnesses brought on by pathogens like Pythium, Fusarium, and Phytophthora since there are no natural soil organisms present [2]. In controlling pests and illnesses, however, the use of biological control agents (BCAs) has showed promise. Beneficial nematodes, parasitoids, and predatory insects are examples of BCAs that may efficiently manage pest populations and lessen the need for chemical pesticides [8].

5.1.3 Cost and energy consumption: Evaluating economic and environmental impacts

The results of the study suggest that producers should take the energy and financial costs of hydroponic systems into account. When compared to conventional soil-based farming, hydroponics can have greater initial investment costs, but it may also have longer-term advantages in terms of improved production and resource efficiency [9]. Hydroponics may use less energy by using energy-efficient technology like LED lighting, High-Pressure Sodium (HPS), Metal Halide (MH), and Fluorescent lighting systems (see Table 2).

Table 1. Comparison of nutrient content in synthetic and organic nutrient solutions

Nutrient	Synthetic Nutrient Solution (ppm)	Organic Nutrient Solution (ppm)
Nitrogen (N)	200	150-250
Phosphorus (P)	100	80-120
Potassium (K)	200	150-250
Calcium (Ca)	100	80-120
Magnesium (Mg)	50	40-60
Iron (Fe)	2	02
Zinc (Zn)	0.2	0.2-0.4
Copper (Cu)	0.05	0.05-0.1
Manganese (Mn)	0.5	0.4-0.6
Boron (B)	0.5	0.4-0.6

Table 2. Comparison of energy consumption in different lighting systems

Lighting System	Energy Consumption (W/m2)
High-Pressure Sodium (HPS)	400-600
Metal Halide (MH)	400-600
Light Emitting Diode (LED)	200-400
Fluorescent	40-80

5.2 Present Issues in Aeroponics

5.2.1 Root health and nutrient delivery: Challenges and remedial measures

The study's conclusions highlight the significance of preserving ideal root health and making sure that nutrients are delivered effectively in aeroponic systems. Aeroponic root development and nutrient absorption might be severely impacted by an inadequate moisture supply and an insufficient oxygen level [4]. Aeroponics can benefit from novel methods that increase nutrient delivery and promote root health, such as the use of ultrasonic misters and small droplet sizes [10].

5.2.2 Maintenance and system complexity: A thorough examination

Due to their complicated design and complexity, aeroponic devices require attentive upkeep. The results of the study emphasise the significance of routine maintenance and monitoring procedures to guarantee the efficient functioning of aeroponic systems. Monitoring nutrient contents, pH levels, misting system efficiency, avoiding clogging, and keeping the root chamber clean are important maintenance duties (see Table 3; [11]).

5.2.3 Initial investment costs: Comparative analysis and considerations

The results of the study suggest that the initial investment expenses for setting up aeroponic systems may be greater than those for conventional agricultural techniques (see Table 4). However, aeroponics' potential advantages, including as increased agricultural yields, decreased water use, and greater resource efficiency, can help ensure the long-term survival of an industry [11]. When evaluating the financial viability of aeroponic systems, growers must take into account a number of variables, including crop selection, market demand, and regional economic conditions [12].

Table 3. Aeroponic system maintenance tasks and best practices

Maintenance Tasks	Recommended Frequency
Nutrient concentration check	Weekly
pH level monitoring	Daily
Misting system performance	Daily
Root chamber cleaning	Every 1-2 weeks
System inspections	Monthly

Table 4. Comparative analysis of initial investment costs

Cost Factors	Aeroponics ($)	Traditional Farming ($)
Infrastructure and Equipment	50,000 - 100,000	10,000 - 30,000
Planting Materials	5,000 - 10,000	2,000 - 5,000
Labour Costs	20,000 - 30,000	10,000 - 20,000
Total Investment	75,000 - 140,000	22,000 - 55,000

Table 5. Key water quality parameters in aquaponics

Parameter	Ideal Range	Potential Impacts
pH	6.8 - 7.2	pH deviations can affect nutrient availability
Temperature	20 - 25°C (68 - 77°F)	Extreme temperatures can stress fish and plants
Dissolved Oxygen	>5 mg/L	Low oxygen levels can harm fish and plants
Ammonia	<0.5 mg/L	High ammonia levels are toxic to fish

5.3 Present Issues in Aquaponics

5.3.1 Maintaining water quality: Parameters, monitoring, and control strategies

In order to sustain the health and wellbeing of both fish and plants in aquaponic systems, the research findings emphasise the need of preserving water quality. According to Love et al. [5], important factors impacting water quality in aquaponics include pH, temperature, dissolved oxygen, ammonia, nitrite, and nitrate levels. Maintaining water quality and avoiding negative impacts on fish and plants may be achieved by using management measures, such as biofiltration, to transform hazardous ammonia and nitrite into less dangerous nitrate [13].

5.3.2 Balancing fish and plant health: Achieving optimal equilibrium

The study's findings show how difficult it is to keep fish and plant health in an equilibrium in aquaponic systems. Water quality and plant development can be adversely affected by imbalances in the availability of nutrients, particularly when excess nutrients from fish waste are present [16]. According to the research, optimising the fish-to-plant ratio and using additional nutrient supplementation methods, like mineralisation tanks or supplemental feeding, can support a healthy nutrient cycle and support the productivity and health of both fish and plants (see Table 6,[13].

5.3.3 Seasonal Considerations: Impacts and Adaptations

The results of the study show that the stability and production of aquaponic systems can be considerably impacted by seasonal fluctuations. The performance of the entire system can be impacted by variables including temperature variations, the availability of natural light, and modifications in fish metabolism [5]. Adaptive methods might be used to lessen the seasonal difficulties. The system design may need to be adjusted, temperature control technologies may be used, and extra heating or cooling systems may be added [13].

5.4 Introducing Bioponics-Based Organic Products

5.4.1 Organic nutrient sources: Broadening the spectrum

To increase nutritional diversity and plant health, bioponics systems use a variety of organic fertiliser sources. According to the research results, compost teas made from organic waste that has been composted can offer vital nutrients, healthy bacteria, and organic matter, all of which can benefit the health of the soil and plants (see Table 7,[14]). Natural fertilisers are frequently employed in bioponics to replenish nutritional requirements and encourage plant development, such as seaweed extracts, fish emulsion, and bone meal [15]. Plant-based extracts, made from diverse plant components, can be used as nutrient-rich solutions because they include phytochemicals and trace elements that boost a plant's resistance to disease and resilience.

5.4.2 Natural disease and pest control: Harnessing ecological approaches

Bioponics systems emphasise the use of organic pest and disease management techniques. The study's conclusions demonstrate the potential of advantageous microorganisms and biological pest controllers to fight illnesses and pests while reducing dependency on chemical pesticides. In addition to promoting plant development and suppressing the growth of harmful microbes, beneficial microorganisms can colonise the rhizosphere, including Trichoderma and Bacillus species (see Table 8, [15]). By preying on or parasitising pest populations, biological control agents such as predatory insects, parasitoids, and nematodes can efficiently reduce pest populations [14]. According to the research, incorporating these ecological strategies into bioponic systems can result in long-term, ecologically friendly methods to managing illness and pests.

Table 6. Fish-to-plant ratio and nutrient supplementation techniques

Fish-to-Plant Ratio	Recommended Range
Tilapia	1:1 - 1:2
Trout	1:3 - 1:4
Lettuce	0.25 - 0.5 kg/m²
Tomatoes	0.2 - 0.4 kg/m²
Herbs	0.1 - 0.2 kg/m²

Table 7. Organic nutrient sources in bioponics systems

Organic Nutrient Sources	Examples
Compost Teas	Composted organic materials
Natural Fertilizers	Seaweed extracts, fish emulsion, bone meal
Plant-Based Extracts	Extracts from various plant parts

Table 8. Natural disease and pest control methods in bioponics systems

Natural Disease and Pest Control Methods	Examples
Beneficial Microorganisms	Trichoderma, Bacillus species
Biological Control Agents	Predatory insects, parasitoids, nematodes

Table 9. Sustainable resource utilization strategies in bioponics systems

Sustainable Resource Utilization Strategies	Examples
Organic Waste Management	Composting systems
Water Conservation Techniques	Efficient irrigation systems
Energy-Efficient Practices	Renewable energy sources

5.4.3 Sustainable Resource Utilization: Maximising Efficiency and Minimizing Environmental Footprint

The research's conclusions, which are summarised in Table 9, highlight the significance of maximising resource efficiency and reducing the environmental impact of bioponics-based organic farming. The management of organic waste is essential to the efficient use of natural resources. According to the study, composting systems may be used to recycle organic waste and produce compost that is rich in nutrients for bioponics farming [16]. Bioponics can use less water by applying water conservation strategies such efficient irrigation systems and water recirculation [17]. Energy-efficient procedures help reduce the energy consumption and environmental effect of bioponics activities, including the utilisation of renewable energy sources and optimising lighting and climate control systems [16].

5.5 Comparative Analysis: Bioponics vs. Conventional Systems

This section compares traditional hydroponic, aeroponic, and aquaponic systems with organic systems based on bioponics (see Table 10). The study's conclusions assess bioponics' benefits and drawbacks while highlighting its potential as a sustainable substitute. The advantages of bioponic systems over conventional ones are numerous. In order to provide a wider range of minerals and micronutrients for plant development, it prioritises organic nutrient sources [18]. Ecological methods of disease and pest management lessen the need for synthetic pesticides and encourage the use of sustainable practises [10]. The incorporation of sustainable resource utilisation techniques into bioponics systems also helps to reduce the negative effects on the environment and improve resource efficiency [16].

Table 10. Comparative analysis: Bioponics vs. conventional systems

Aspect	Bioponics	Conventional Systems
Organic Nutrient Sources	Broader spectrum of nutrients	Reliance on synthetic nutrient solutions
Disease and Pest Control	Ecological approaches, reduced pesticide use	Reliance on synthetic pesticides
Sustainable Resource Utilisation	Minimised environmental impact, resource efficiency	Varies across systems
Availability and Consistency of Nutrients	Challenges in large-scale production	Relatively stable nutrient availability
Pest Management	Requires careful monitoring and management	Reliance on pesticides
Initial Investment Costs	Higher initial investment costs	Varies across systems

Bioponics does, however, have its limits. According to the study's findings, producing food using bioponics on a wide scale may be complicated by the availability and constancy of organic nutrient supplies [19]. To guarantee that biological control agents are successful, thorough monitoring and management are necessary [20]. Additionally, the upfront expenses of creating bioponics systems may be greater than those of conventional systems, necessitating careful financial planning [21]. Despite these drawbacks, the research indicates that bioponics has the potential to provide ecologically benign and sustainable alternatives to traditional systems, advancing organic agricultural techniques.

VIRENXIA's Bioponics Product Range Development

- VIRENXIA's Proprietary Bioponics Product based cultivation, developed under the Farmics Brand, involves the use of certified-organic nutrients in a hydroponic solution along with a substrate.
- This was developed based on 100% sustainable agricultural frameworks. The goal is to give less nitrogen to the plant, and shift the balance in favour of the flowering and fruiting stages, rather than the vegetative growth
- It is possible to grow organic produce using hydroponic technologies.
- Is a very economical way of cultivation since the consumption of water and nutrients, is a fraction of the one needed by **any** other growing technique

Advantages of VIRENXIA Bioponics

- Quality. The harvest tastes better with more nutritional value, than organically soil grown produce. This since the Product and bioponics techniques, removes barriers that limit plant growth.
- Genetic Potential. The plant can express its full genetic potential with our developed Product.
- Turnover. Is much faster than in soil, which leads to more crops per year in a bioponics system, than organic soil.
- Microbial Stimulation. Its large microbial population becomes a formidable barrier against pathogens. Roots are hence protected effectively by an army of beneficial organisms where no pathogens develop
- Roots. Bioponic plants grow roots that are sturdier

VIRENXIA's Bioponics – Studies with Indian Institute of Technology Delhi (IITD) undertaken

Study with IITD was undertaken in 2021-22 "To evaluate the potential of selected biomass as source of plant nutrients focusing on developing liquid nutrient solution for agricultural applications"

The Project aimed to meet global food production by developing an organic and sustainable solution that could help provide a scalable and transferable solution to food and nutrition security in developing and arid countries like India and GCC.

Apart from the excess chemical and soil pollution problem, the water crisis is a major problem for arid countries such as UAE as well as developing countries like India. Agriculture consumes more water than any other source and wastes much of that due to inefficiency. Hence, more emphasis should be given to new agriculture verticals such as Bioponics which uses 90% less water, 50% less fertilizer, better nutrient value, stress resistance, require less space, an ability to grow crops on marginal and degraded land and the right step towards Climate Smart Sustainable Agriculture (CSSA).

Low-cost organic formulation design and development by VIRENXIA, for vertical and soil less farming demonstrated at IIT Delhi, are inspired by the vision of transformational change in rural agriculture development processes, by leveraging institutional knowledge to build the architecture of an Inclusive India.

Unlike hydroponics, bioponics is a method of growing plants using a nutrient solution of natural origin in water without soil. It is a technology designed for arid countries in 'The Cooperation Council for the Arab States of the Gulf' (GCC), also developing countries like India where farming is dependent on natural sources, where it is advantageous over soil-based vegetable production in that it conserves water, avoids soil-borne diseases, makes vegetable production possible even in areas with poor soil fertility and generally enhances vegetable production and quality.

This development comes as a relief to communities with less financial abilities to access hydroponics via organic sources for plant nutritional requirements. This is considering that the use of conventional fertilizers for agriculture is relatively expensive worldwide.

To help develop the proposed solution to the aforementioned problem, this Project employed the translational research & development methodology. The translational research & development methodology is a structured framework based on best practices that greatly improve the likelihood of delivering a product in time, within budget, and to specification. It explains how to initiate and plan, execute, and close a translational research & development project conducted within an academic institution with the intent of bringing a product to market.

This project with IITD involved formulation development and final production that is highly nutritious containing all the nutrition required for optimum growth of crops that can be used as an alternative for hydroponic, aquaponics, aeroponics, and sustainable farming.

The mission of this trial is to enable higher educational institutions to work for vertical farmers or those farmers who are willing to switch into soil-less farming in India as well in arid countries under GCC. By identifying low-cost organic material for Agri input development, appropriate solutions for accelerating sustainable crop growth can be achieved. It also aims to create a virtuous cycle between society and an inclusive academic system, by providing knowledge and practices for emerging farmers and upgrading the capabilities of agriculture sectors, in responding to the development needs of rural India.

The prospect of using twenty different organic nutrients as an alternative source of nutrients for hydroponics, aeroponics, aquaponics, and traditional farming was validated.

The methodology developed by VIRENXIA and validated by IITD to produce high quality, nutritional, and flavourful vegetables for consumption in both local and international markets was found successful.

The primary and secondary research to validate the ingredients for designing of formulations was found most accurate.

The optimisation and development of the formulations for Bioponics, aquaponics, aeroponics to produce high-quality crops for both the national and international market year-round was undertaken and found correct.

Biophysicochemical characterisation of developed formulations was undertaken successfully.

R&D selects the appropriate raw materials based on functionality. Functionality can encompass multiple areas, such as providing identified characteristics of the finished product (binders, thickeners, type of resin for plastic packaging, etc.), organoleptic characteristics (flavour, colour, aroma, texture), product safety characteristics (to lower the pH or water activity), and bio-preservatives (extension of shelf life, color, or flavour retention, etc.)

Individual ingredients, which form the foundation of the finished product, were also examined for a variety of characteristics, including physical appearance, water-solubility, leaching property, toxicity, cost, year-round availability, nutritional value, and shelf life. Apart from these, potential biological, chemical, and physical hazards associated with the raw material, prohibition in agriculture/horticulture use, and if additional measures are circumnavigated to prevent potential safety issues for the employees and product must all be considered when screening raw material. As a result of this study, we were able to choose the best biomass for the final product, which will ultimately increase agricultural productivity.

Extensive primary and secondary research is carried out for the selection of suitable raw materials for formulation development. Several factors were considered for raw material selection such as unique and complex materials, global sourcing, handling methods, locations, regulations, etc.

Formulation centered on extracting specific nutrients from biomass required for plant growth from raw materials. Water was used for the extraction, along with time and centrifugal force. Biomasses will be blended for different levels of NPK as well as other nutrients found naturally in biomass.

Plant-derived biomass leachate produced an optimum balance of macro, micronutrients, pH, EC, trace elements, humic, fulvic acids, and plant hormones. Furthermore, because biomass does not often include chlorides over what the plant requires, there is no build-up of EC electrical conductivity in bioponics. As a result, there will be no need to discharge water in bioponics to preserve equilibrium.

This R&D analysis determined that all the selected biomass except deoiled cake, and cow dung, had certain functionality in terms of providing identified characteristics to the finished product such as solubility (Molasses), binders (pulse flour), thickeners (egg shell powder, Banana peel powder), organoleptic characteristics (flavour, colour, aroma, texture), product safety characteristics (to lower the pH or water activity), and preservatives such as molasses, neem seed powder (extension of shelf life, colour, or flavor retention, etc.).

Due to its oil content, the deoiled cake could not be mixed with other ingredients. If this biomass is chosen for the end product, the manufacturing team must ensure that the raw material is properly washed, which may necessitate more resources and time. All of the biomass samples were tested for shelf life, and it was discovered that, except for the deoiled cake, all of them were able to maintain their physicochemical characteristics, implying that, under proper storage circumstances, they can be easily preserved for up to 18 months.

Both molasses and jaggery are sources of sugar and other micronutrients in terms of nutrition, thus one can be avoided. Other characteristics such as pH, water-solubility, flavour, and odour were likewise identical between the two. However, because jaggery was more expensive than molasses in terms of cost, molasses should be used for final product development.

We also discovered that formulations were recorded with a high microbial load due to cow dung. Cow dung, a bovine animal's excrement, is a cheap and readily available bio-resource on our planet. In India, cow dung has long been used for a variety of purposes, including fire, insect repellant, and washing. Cow dung, on the other hand, contains a wide range of microorganisms that may or may not be useful to the product if stored for an extended period. The high ammonia level in anaerobic conditions was shown to be related to a high microbial load in the formulation, according to the study. High ammonia generation later in the process may cause problems for the final product by decreasing pH, increasing EC, and forming other metabolites. Physical traits such as unpleasant odour and high viscosity may also be present. Physical qualities such as unpleasant odour and high viscosity can also be disadvantaged.

Neem seed powder is found as excellent biomass as it possesses Insect /bacterial / fungal pathogen repelling compounds azadirachthin, meliantriol, and salannin, which inhibit the maturation or feeding ability of insect pests without having any adverse effects on birds and mammals. It will save the cost of synthetic pesticides. Its year-round availability, lower cost make it suitable for all five formulations. It is advisable to use this biomass for all formulations as it will improve insecticidal/pesticide value as well as shelf life.

Apart from having a pleasant aroma, periwinkle and tuberose are known to be high in potassium, iron, magnesium, phosphorus, copper, and selenium. However, it was discovered that these requirements can be met by other raw materials such as amaranthus and pulses, which are readily available and inexpensive all year.

Plant vitamins requirements such as folates, vitamin B6 (pyridoxine), riboflavin, thiamin (vitamin B-1), and niacin can be fulfilled by Amaranthus as it contains an ample amount of the same. In addition to this, fresh 100 g of leaf amaranth contains 29% of iron. Iron is an essential trace element required by the plant body for several functions.

Both gypsum and eggshell powder are good sources of calcium. Pure gypsum contains 23.3% calcium (Ca) and 18.6% sulfur (S). Gypsum is moderately soluble in water (2.5 g per L) or approximately 200 times greater than lime ($CaCO_3$). This makes the calcium in gypsum more mobile than the calcium in lime and allows it to more easily move through the soil profile.

A great quantity of eggshells is generated as bio-waste all over the world each day. Not only does the odour of eggshell provide a site for flies and abrasiveness, but also many useful materials are lost.

Similarly eggshell powder, apart from high calcium content, will enrich the pH content. Since both the biomass are fulfilling the same nutritional requirement, the eggshell powder can be removed from the potential list as it may create odour issue problems in the product if not processed properly. In addition to this, leaching time of eggshell powder was slow as compared to gypsum. Another concern is solubility wherein eggshell powder we found less and slowly soluble in water which makes it unsuitable for hydroponics. Based on physical and chemical (reported scientifically) characteristics, it is recommended to include seaweed powder in all formulations. Another basic material is banana peel powder, which is a good source of natural organic potassium and helps the plant transfer water and nutrients between its cells. Its use, according to studies, boosts the plant's ability to blossom and fruit. It also aids in the expansion of the fruit's size and the improvement of the form of the lingers in the bunch. It also protects the plants from a variety of illnesses and strengthens the stem, preventing the plants from toppling over, as well as drought resistance.

Azolla is a floating pteridophyte, which contains as endosymbiont the nitrogen-fixing cyanobacterium Anabaena azollae (Nostocaceae family). Widely cultivated in the Asian regions. It can easily be added to the formulation due to its nitrogen content which can increase agriculture productivity. Aquaponics uses the best of all the growing techniques, utilising the waste of fish that is rich in nitrogen.

Overall it was concluded that except tuberose, periwinkle, and deoiled cake, all other selected biomass were suitable for formulation development.

The study with IITD provided robust scientific bases to support the development of innovative Agri input solutions for sustainable and vertical farming. The research demonstrated a link between the chemical features of formulation and the plant physiological responses they can favourably trigger. This methodical approach, which starts with targeted access to raw materials and ends with product development, aids in the effective transformation of potential natural active components into high-quality nutrient solutions.

Finally, significant field trial experience, as well as know-how acquisition in the formulation and biological action, are and will continue to be critical in meeting the needs of current and future professional agriculture. The mission of this trial was to also enable higher educational institutions to work for vertical farmers or those farmers who are willing to switch into soil-less farming in India as well in arid countries under GCC. By identifying low-cost organic material for Agri input development, appropriate solutions for accelerating sustainable crop growth can be achieved. It also aims to create a virtuous cycle between society and an inclusive academic system, by providing knowledge and practices for emerging farmers and upgrading the capabilities of agriculture sectors, in responding to the development needs of rural India.

With the year long trials at IITD and based on Project findings, it was concluded that biomass advised by VIRENXIA is rich in nutrition, has high shelf life, less caking, flowability, non-carcinogenic, hygroscopic nature, and safe for agriculture application. Hence the selected biomass are very much suitable with each other, safe to use for formulation development under aerobic conditions.

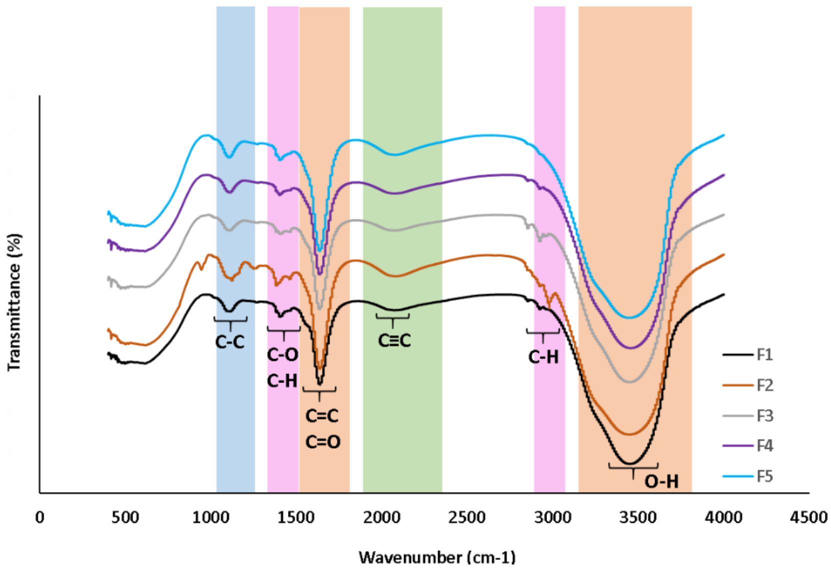

Fig. 2. FTIR Analysis of different formulations

FTIR analysis revealed the existence of similar peaks in all 5 samples indicating the common functional groups present. Generally, peaks between 1000 and 1500 are corresponding to C-H and C-O bond stretch. The peak between 3000 – 3500 generally represents the hydroxyl group present in these products which were observed in all products tested. Peaks at 2940, 1515, and 898 cm-1, indicate the characteristic –CH stretching vibrations of aliphatic groups, aromatic skeletal of lignin, phenolics, and β-glycosidic structures plant cell wall or decaying remnants of plants. Peaks at 2940, 1515, and 898 cm-1 in Fig. 2, indicate the characteristic –CH stretching vibrations of aliphatic groups, aromatic skeletal of lignin, phenolics, and β-glycosidic structures plant cell wall or decaying remnants of plants. Infrared analyses did reveal that formulation composed of carboxylic acids, ketones, and phenolic-OH) groups and polysaccharide-like components.

Furthermore, a strong aromatic C=C and an aromatic C-C absorption band at 1640 to 1610 cm-1 appeared in the case of all formulations. All five formulations exhibited a significant band indicative of C=O stretching of amides and quinones at 1500 cm-1 to 1550 cm-1. Other bands at 1420 to 1390 cm-1 common to all formulations except F5 are attributed to -OH deformation. The spectra of all formulations also showed the peaks and/or bands at1365–1402 cm–1(C– H deformation of CH2 and CH3, salts of carboxylic acid and/or aliphatic CH), 1229–1230 cm–1(C–O stretching vibrations of esters, ethers, and phenols), and 1088–1095 cm–1 (C–O stretch).

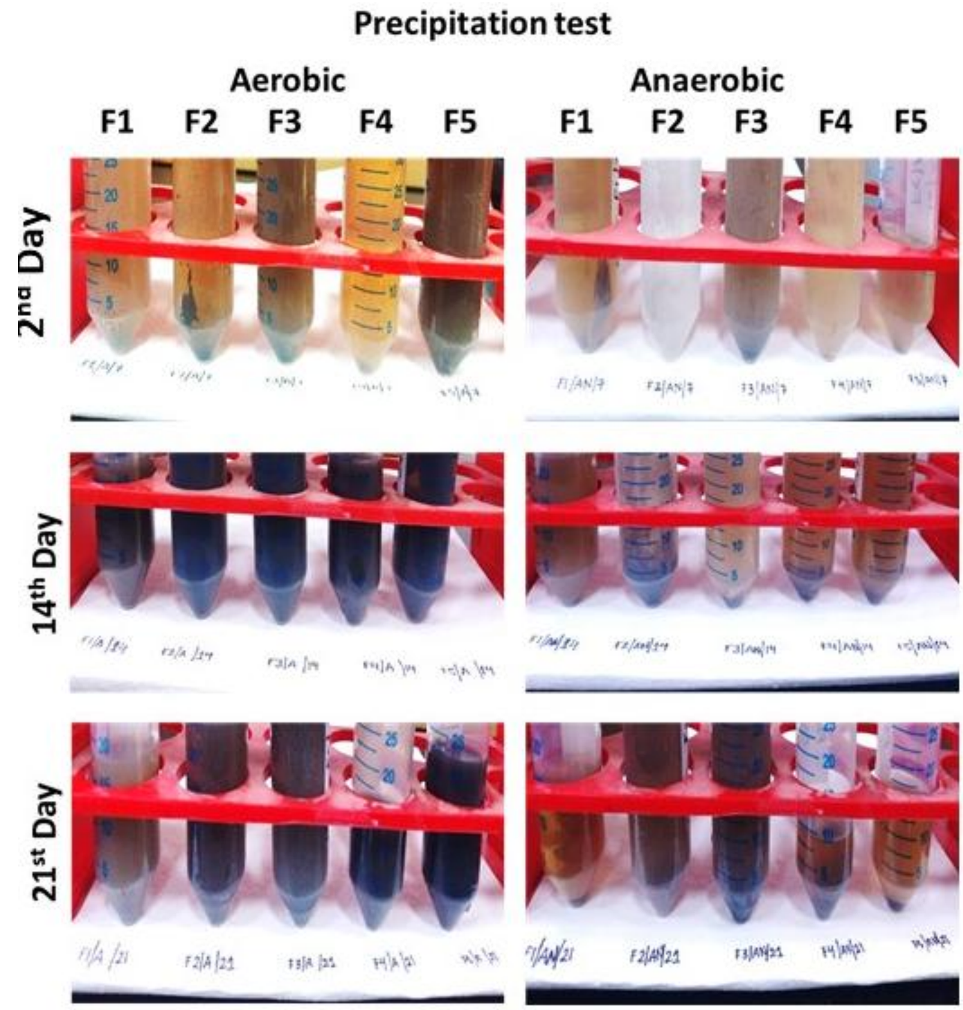

Fig. 3. Analysis of precipitation in different formulations kept at 4°C for 30 days

This test revealed that when stored at 4°C, all of the samples tended to precipitate. When compared to anaerobically treated samples, aerobically treated samples had more precipitation. When a total of 50 ml of precipitation was employed, the volume of precipitation recorded was 3 ml in all cases. When the solution was vigorously shaken, the precipitate dissolved and was visible after a minimum of 24 hours incubation. As a result, even if precipitation was seen, it may be presumed that it can be shaken thoroughly before use as a biostimulant for field applications. Whereas in the case of hydroponic, aquaponics, and aeroponics, it shall be filtered thoroughly, else it may clog the system.

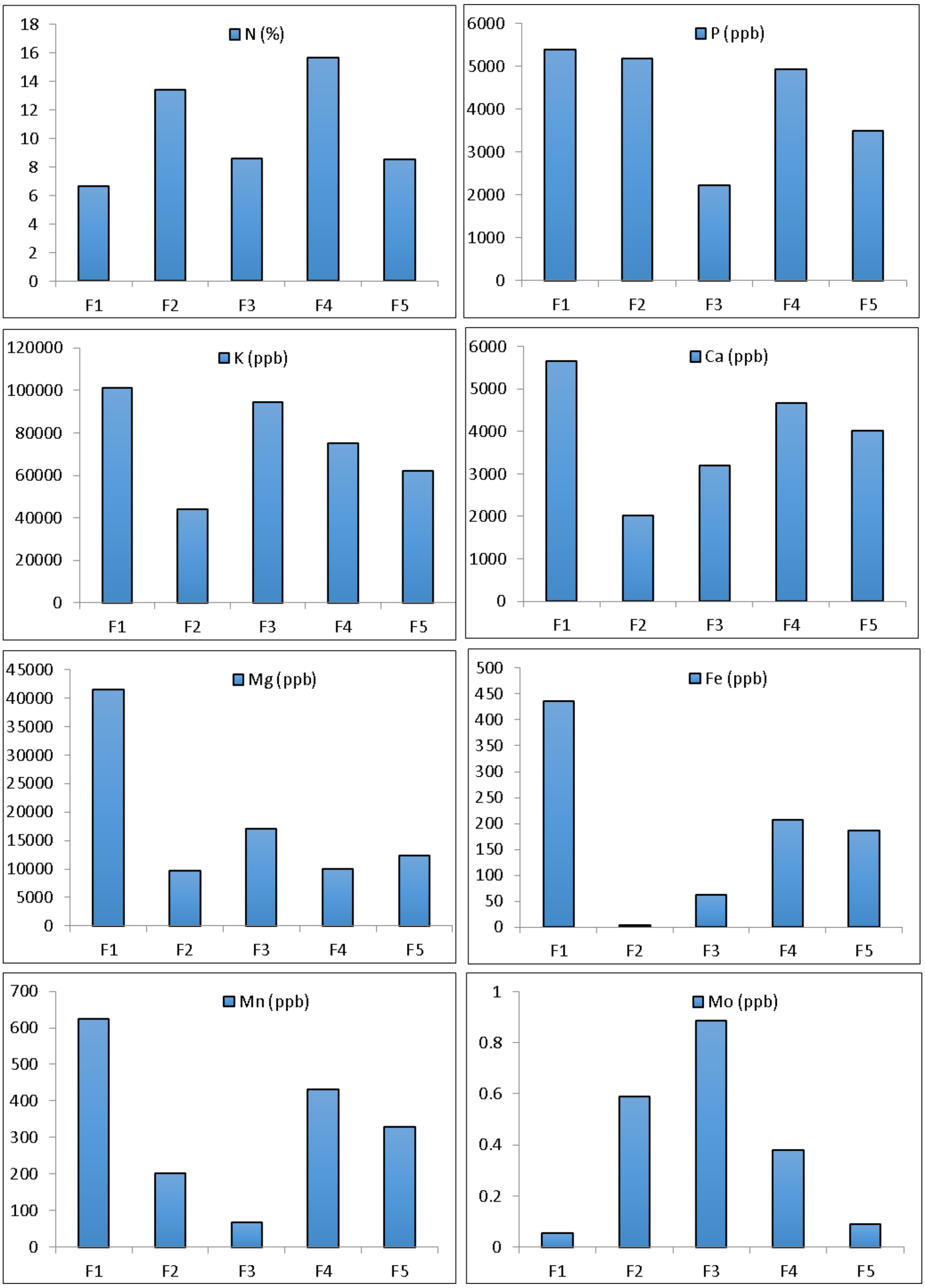

Fig. 4. Micro and Macro nutrients present in selected formulations

Nutrient composition analysis indicated the variations in their composition between the 5 tested samples (Fig. 4). F2 and F4 were found to be rich in nitrogen (N) compared to other formulations. Similarly, Phosphorus (P) was found higher in F1, F2, and F4. However, F2 was lower in their K content compared to other formulations. The highest K of 100000 ppb was recorded by F1. Calcium content was found varying between 2000 to 6000 ppb. F1 recorded a significantly higher content of Mg (>40000 ppb), whereas other formulations recorded between 5000 to 15000 ppb. Further F1 recorded the highest of 430 ppb Fe and 620 ppb Mn. However, F3 recorded higher Mo (0.9 ppb).

Overall, these formulations were found to be a good source of macro and micronutrients for plant growth.

All five formulations recorded particle sizes between 100 to 5000 nm. The least of 544 nm (Average size) has been reported by F1 followed by F4 (576 nm), F2 (620 nm), and F3 (720.0 nm). Polydispersity index (PDI) is a representation of the distribution of size populations within a given sample. The numerical value of PDI ranges from 0.0 (for a perfectly uniform sample concerning the particle size) to 1.0 (for a highly polydisperse sample with multiple particle size populations). Lest PDI values were recorded by F3 (PDI: 0.192) indicating the better uniformity in particle size in comparison to other formulations studied.

Small particle size (in nm range) generated due to sonication followed by filtration process further added a beneficial attribute to both the extracts. Reduced particle size help to increase their surface area and makes available their ions to enter into ionic and donor-acceptor interactions, form hydrogen bonds, actively participate in sorption processes, increase organic matter mobility, interactions with clay surfaces, and aggregation in natural environments.

Cumulant Results

Z-Avg (nm):	752.0
Pd Index:	0.453
Pd (nm):	505.9
%Pd:	67.3
Derived kcps:	1339.8

Distribution Results

	Size (d.nm):	**% Int**	**σ**	**%Pd**
Peak 1:	500.9	74.3	106.3	21.2
Peak 2:	4665	25.7	781.6	16.8
Peak 3:	0.000	0.0	0.000	0

Undersize Results

Di (%)	**Size (d.nm):**
50	544
90	5000
95	5480

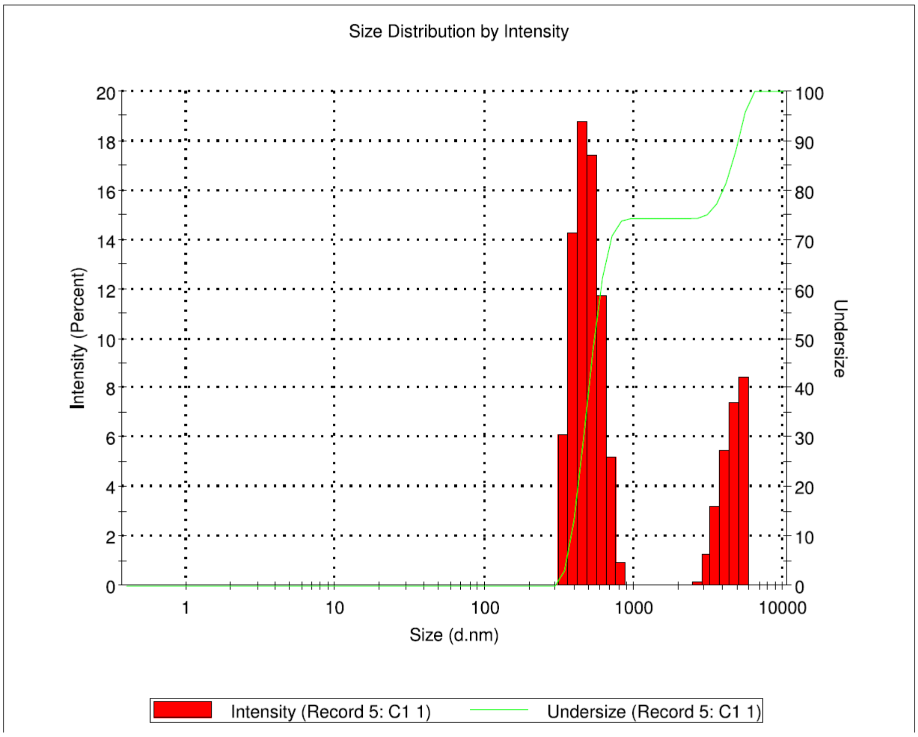

Fig. 5. Particle size distribution in a tested formulation

Table 11. Fold increase/decrease in root length, shoot length and germination Radish seedlings upon treatment with formulations

		F1/A			F2/A			F3/A			F4/A			F5/A		
	Conc	**Day 2**	**Day 14**	**Day 21**	**Day 2**	**Day 14**	**Day 21**	**Day 2**	**Day 14**	**Day 21**	**Day 2**	**Day 14**	**Day 21**	**Day 2**	**Day 14**	**Day 21**
F1/A -RL	Stock	-0.406	-0.355	0.452	-0.166	0.650	0.772	0.135	0.514	0.514	0.582	0.286	0.750	0.415	-0.050	0.489
	10^{-1}	0.183	0.340	0.365	0.421	0.429	0.198	0.261	0.413	0.413	0.509	0.387	0.387	0.228	0.317	0.522
	10^{-2}	0.039	0.017	0.761	0.039	0.555	0.550	0.052	0.455	0.667	0.390	0.000	0.250	0.378	0.455	0.429
F1/A -SL	Stock	-0.546	-0.560	-0.129	-0.227	0.066	-0.029	-0.076	-0.006	-0.111	-0.004	-0.049	-0.021	0.007	-0.208	-0.140
	10^{-1}	-0.028	0.051	0.070	-0.081	0.188	-0.159	0.224	0.215	0.095	0.008	-0.167	0.269	-0.085	0.144	0.226
	10^{-2}	0.062	0.092	0.281	0.063	-0.205	-0.045	0.083	0.052	0.134	0.174	0.060	0.034	0.150	0.282	0.140
F1/A -GE %	Stock	-0.200	-0.450	0.050	0.100	0.050	0.150	0.150	-0.100	0.150	0.250	0.050	0.250	0.200	0.000	0.150
	10^{-1}	0.050	0.250	0.150	0.050	0.050	0.200	0.150	0.000	0.100	0.100	0.150	0.150	0.150	0.050	0.150
	10^{-2}	-0.050	0.000	0.150	0.050	0.000	0.000	0.050	0.100	0.050	0.050	-0.150	-0.200	0.000	-0.150	0.050
F1/AN -RL	Stock	-0.593	-0.355	-0.464	0.400	0.164	-0.132	-0.722	-0.638	-1.000	0.094	-0.180	0.198	-0.447	-0.908	-0.500
	10^{-1}	0.183	0.340	0.270	0.000	0.367	0.280	-0.126	0.370	0.323	-0.082	0.517	0.550	0.052	0.143	0.060
	10^{-2}	0.039	0.105	-0.053	0.525	0.525	0.025	0.029	0.481	0.013	0.447	0.564	0.400	0.029	0.369	0.145
F1/AN -SL	Stock	-0.360	-0.834	-0.635	0.053	-0.069	-0.300	-0.076	-0.765	-1.000	0.045	-0.040	-0.163	-0.480	-0.891	-0.686
	10^{-1}	-0.370	-0.304	-0.346	-0.095	-0.267	-0.053	-0.049	-0.211	0.037	-0.155	-0.221	0.044	-0.057	0.006	-0.103
	10^{-2}	0.193	0.092	-0.172	0.277	-0.209	-0.031	-0.066	-0.276	0.117	0.129	-0.261	0.075	0.041	0.031	0.113
F1/AN -GE %	Stock	0.000	-0.850	-0.650	0.000	0.050	-0.150	-0.100	-0.600	-1.000	-0.100	0.100	0.000	0.100	-0.450	-0.700
	10^{-1}	-0.050	0.100	0.100	0.050	0.150	0.250	0.050	0.100	0.200	0.000	0.050	0.250	0.050	0.050	0.050
	10^{-2}	0.050	-0.150	-0.050	0.000	0.000	0.000	-0.150	0.050	0.000	-0.050	0.100	-0.150	-0.050	0.050	0.100

**Green : Increase, Yellow : Neutral, Red : Decrease*

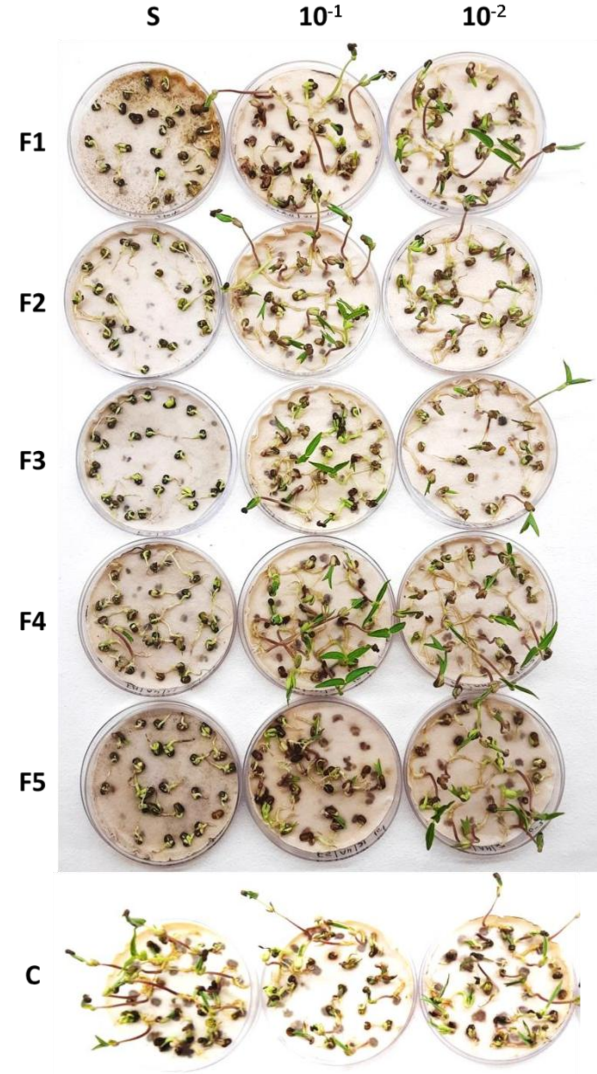

Fig. 6. Phytotoxicity analysis of formulations 2nd, 14th and 21st day on Greengram seedlings under aerobic and anaerobic conditions

Further different concentrations of formulations were tested for their phytotoxicity or plant growth simulation/promoting potential. Three crops, Greengram, Radish, and Mustard were selected for the experiment. In the case of green gram, the root length of seedlings was significantly increased by F1, F2, F3, and F4 samples incubated under aerobic conditions. Whereas shoot length was significantly decreased in stocks solutions of all aerobic samples. However, dilutions recorded an increase in shoot length. Seed germination was significantly affected in any of the dilutions tested. Hence the Bioponics formulations made excelled in the phytotoxicity tests too.

Formulations incubated under aerobic conditions were found significantly increasing the root length in dilutions over stock solution. F2, F3 and F4 were significant in increasing the root length. However, stock solutions were found toxic to shoot growth which was found reduced with dilutions. Also, a small range of seed germination was found increased with dilutions of all formulations. Samples treated with anaerobic formulations recorded significantly decrease in root length, shoot length and seed germination when stock solutions were used. However, with dilutions, root length was significantly increased. Overall, aerobically incubated formulations were found better in improving the green gram seedlings and validated VIRENXIA's Bioponics formulations

UV-Visible spectra: In general, not many significant variations were observed with all the formulations when observed at a visible range between 450 to 950 nm. However, a significant variation among formulations was observed towards 450 to 350 nm. As we used complex combinations of biomass while preparing formulations, the increased absorbance towards UV range indicated the presence of various molecules of plant origin (possibly, proteins, amino acids, nucleic acids, flavonoids, phenolic compounds, tannins, terpenoids, carotenoids, chlorophyll, and alkaloids).

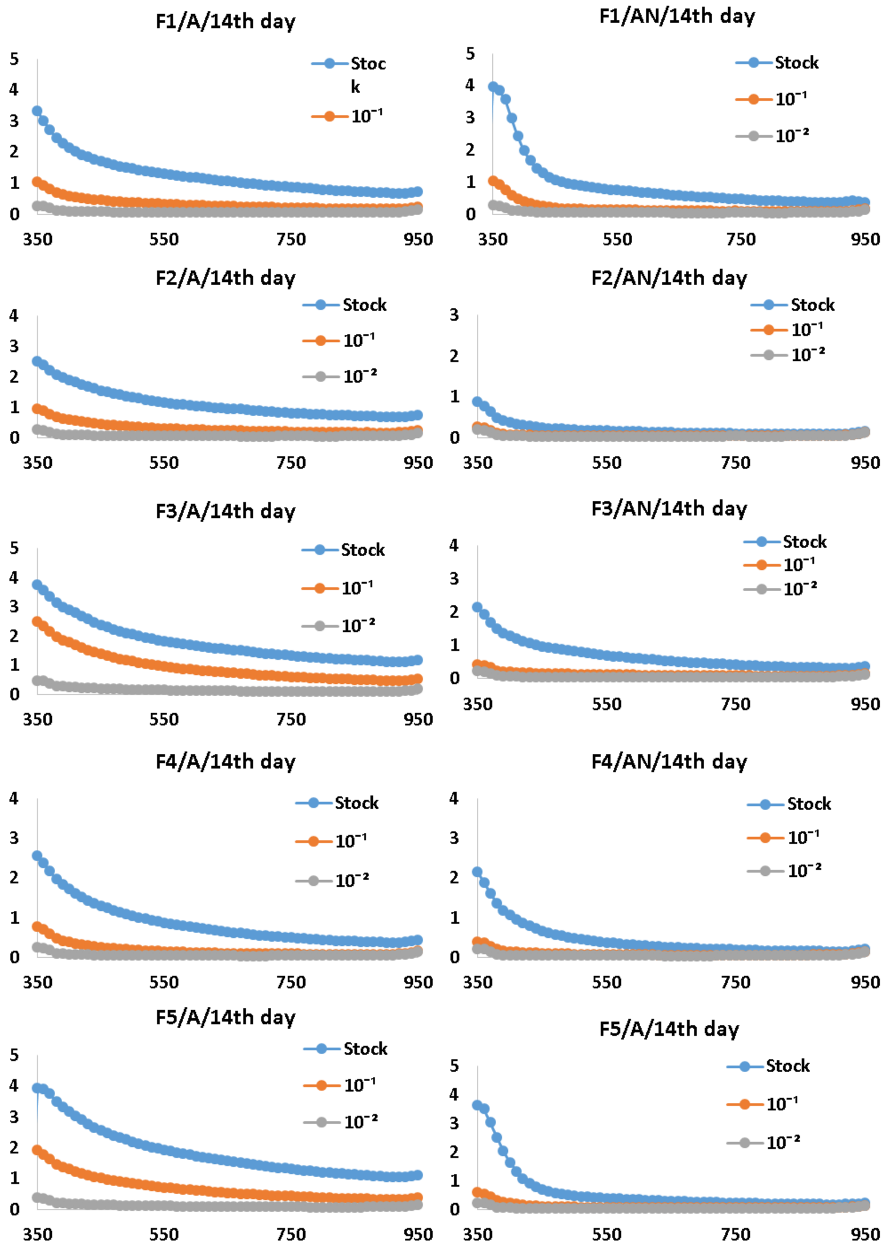

Fig. 7. UV-Visible spectra of the formulations incubated for 14 days

6. CONCLUSION

The current problems in hydroponics, aeroponics, and aquaponics have been investigated and analysed in this study, underlining the significance of resolving these concerns for the development of sustainable agricultural practises. The results have highlighted the necessity of preserving root health and nutrient delivery in aeroponic systems, monitoring water quality and achieving a balance between fish and plant health in aquaponic systems, and optimising resource use in both systems. The use of organic nutrient sources, ecological disease and pest management, and sustainable resource utilisation are only a few benefits of bioponics-based organic systems over conventional ones that have been discovered via comparative investigation.

The results of the study highlight the possibility of bioponics as a long-term replacement for traditional systems. Bioponics presents prospects for boosting plant development, minimising environmental impact, and promoting resource efficiency by fusing organic practices, natural remedies, and ecological techniques. The research has also noted several difficulties, like as the stability and availability of organic nutrition supplies, efficient pest control using biological control agents, and greater upfront expenses.

7. FUTURE DIRECTIONS

Future bioponics and organic farming practises research and innovation opportunities exist in a number of areas. Some possible directions are:

1. **Nutrient Source Development**: Expanded research and development of a variety of inexpensive, easily accessible, and reliable organic nutrient sources that deliver a steady stream of vital nutrients to bioponics systems.
2. **Biological Control Agents:** The discovery of particular strains, comprehension of their interactions with plants and pests, and development of effective application techniques are all part of research on the effectiveness and optimisation of biological control agents for pest management in bioponics.
3. **Scalability and Commercial Viability:** Research on the economic feasibility and scalability of bioponics systems, with an emphasis on lowering startup costs, increasing production effectiveness, and gauging consumer demand for bioponics-based organic goods.
4. **Automation and Technology Integration:** Integration of artificial intelligence, sensor networks, and sophisticated automation technologies to increase bioponics' overall sustainability, efficiency, and productivity while also optimising resource use.
5. **Environmental Impact Assessment:** In-depth examination of bioponics systems' environmental effects, including life cycle analysis, carbon footprint assessment, and analyses of water and energy use, is required to assure their overall sustainability and ecological advantages.
6. The Bioponics formulations devised by VIRENXIA and validated by IITD be used for further research and making novel products ‘Fit for Market’ in the now empty space trajectory.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here:
https://www.sdiarticle5.com/review-history/103034