The Potential of Algal Consortium as an Innovative and Effective Biofertilizer for Sustainable Agriculture in India

Abstract

With increasing agricultural demands and the need to minimize the environmental impacts of chemical fertilizers, algal biofertilizers have emerged as an eco-friendly solution. Algal consortium-based biofertilizers, in particular, hold promise due to their capacity to improve soil health, increase crop yield, and contribute to sustainable agricultural practices. This paper examines the potential of algal consortium as a unique biofertilizer, emphasizing the roles of different algal species, the mechanisms they employ in nutrient enrichment, and the overall impact on soil and plant health. The beneficial mechanisms of plant growth improvement include enhanced availability of nutrients (i.e., N, P, K, Zn and S), phytohormone modulation, biocontrol of phytopathogens and amelioration of biotic and abiotic stresses. This plant-microbe interplay is indispensable for sustainable agriculture and these microbes may perform essential role as an ecological engineer to reduce the use of chemical fertilizers. Various steps involved for production of solid-based or liquid biofertilizer formulation include inoculum preparation, addition of cell protectants such as glycerol, lactose, starch, a good carrier material, proper packaging and best delivery methods. In addition, recent developments of formulation include entrapment/microencapsulation, nano-immobilization of microbial bioinoculants and biofilm-based biofertilizers. Thus, inoculation with beneficial microbes has emerged as an innovative eco-friendly technology to feed global population with available resources. By analyzing the effectiveness of algal consortium-based biofertilizers and comparing them with traditional synthetic fertilizers, this paper highlights their advantages, challenges, and future research directions in sustainable agriculture.

KeyWords: Algal Consortium, Effective Biofertilizer, sustainable agriculture, India

Introduction

The modern agricultural sector faces substantial challenges, including soil degradation, increased pest resistance, and climate change. Chemical fertilizers have long been relied upon to boost crop productivity, but they often lead to environmental degradation, reduce soil fertility over time, and pollute water resources through leaching. Biofertilizers, especially those based on algal consortia, offer a sustainable alternative that can mitigate these issues by enriching soil naturally, enhancing microbial diversity, and promoting plant growth without harmful side effects. Algal biofertilizers leverage the beneficial properties of algae, which are capable of nitrogen fixation, nutrient enrichment, and producing growth-promoting substances. Modern intensive agricultural practices face numerous challenges that pose major threats to global food security. In order to address the nutritional requirements of the ever-increasing world population, chemical fertilizers and pesticides are applied on large scale to increase crop production. However, the injudicious use of agrochemicals has resulted in environmental pollution leading to public health hazards [17,18]. Moreover, agriculture soils are continuously losing their quality and physical properties as well as their chemical (imbalance of nutrients) and biological health. Plant-associated microbes with their plant growth- promoting traits have enormous potential to solve these challenges and play a crucial role in enhancing plant biomass and crop yield (Alobwede et al., 2019). The beneficial mechanisms of plant growth improvement include enhanced nutrient availability, phytohormone modulation, biocontrol of phytopathogens and amelioration of biotic and abiotic stresses. Solid-based or liquid bioinoculant formulation comprises inoculum preparation, addition of cell protectants such as glycerol, lactose, starch, a good carrier material, proper packaging and best delivery methods [15,16]. Recent developments of formulation include entrapment/microencapsulation, nano-immobilization of microbial bioinoculants and biofilm-based biofertilizers.

An algal consortium consists of multiple algal species that work synergistically to enhance soil health and plant growth [19,20]. Such consortia are particularly beneficial as they improve nutrient cycling, increase soil fertility, and provide essential compounds that enhance plant resilience (Gonçalves et al., 2023). This paper explores the potential benefits, challenges, and applications of algal consortium-based biofertilizers.

Algae as Biofertilizers

Algae are versatile microorganisms that exist in various environments, including soil, water, and plant surfaces. They play a crucial role in the ecosystem by fixing nitrogen, producing oxygen, and contributing to the food web. Algae are rich in essential nutrients, such as nitrogen, phosphorus, potassium, and a range of trace elements that are essential for plant growth (Chatterjee, et al., 2017).

Biofertilizers derived from algae offer several advantages, including:

1. **Nitrogen Fixation**: Certain algae, such as cyanobacteria, can fix atmospheric nitrogen, making it available to plants.
2. **Enhanced Soil Fertility**: Algae improve soil structure and nutrient availability.
3. **Plant Growth Promotion**: They produce phytohormones like auxins, gibberellins, and cytokinins, which stimulate plant growth.
4. **Biocontrol Properties**: Some algal species can inhibit pathogens, reducing the need for chemical pesticides.

An algal consortium combines different algal species to enhance these benefits synergistically.

Algal Consortium: Composition and Mechanisms

An effective algal consortium generally includes different algal groups such as cyanobacteria, green algae, and diatoms. Each type contributes distinct benefits that make the consortium more effective as a biofertilizer. For instance:

Cyanobacteria (e.g., Anabaena, Nostoc): These are nitrogen-fixing algae that convert atmospheric nitrogen into forms that plants can use. Cyanobacteria also improve soil moisture retention and structure.

Green Algae (e.g., Chlorella, Scenedesmus): Known for their high nutrient content, green algae release amino acids, vitamins, and enzymes that benefit soil microbes and plants.

Diatoms: These algae have siliceous cell walls that improve soil aeration, structure, and water retention (Gururani et al., 2022).

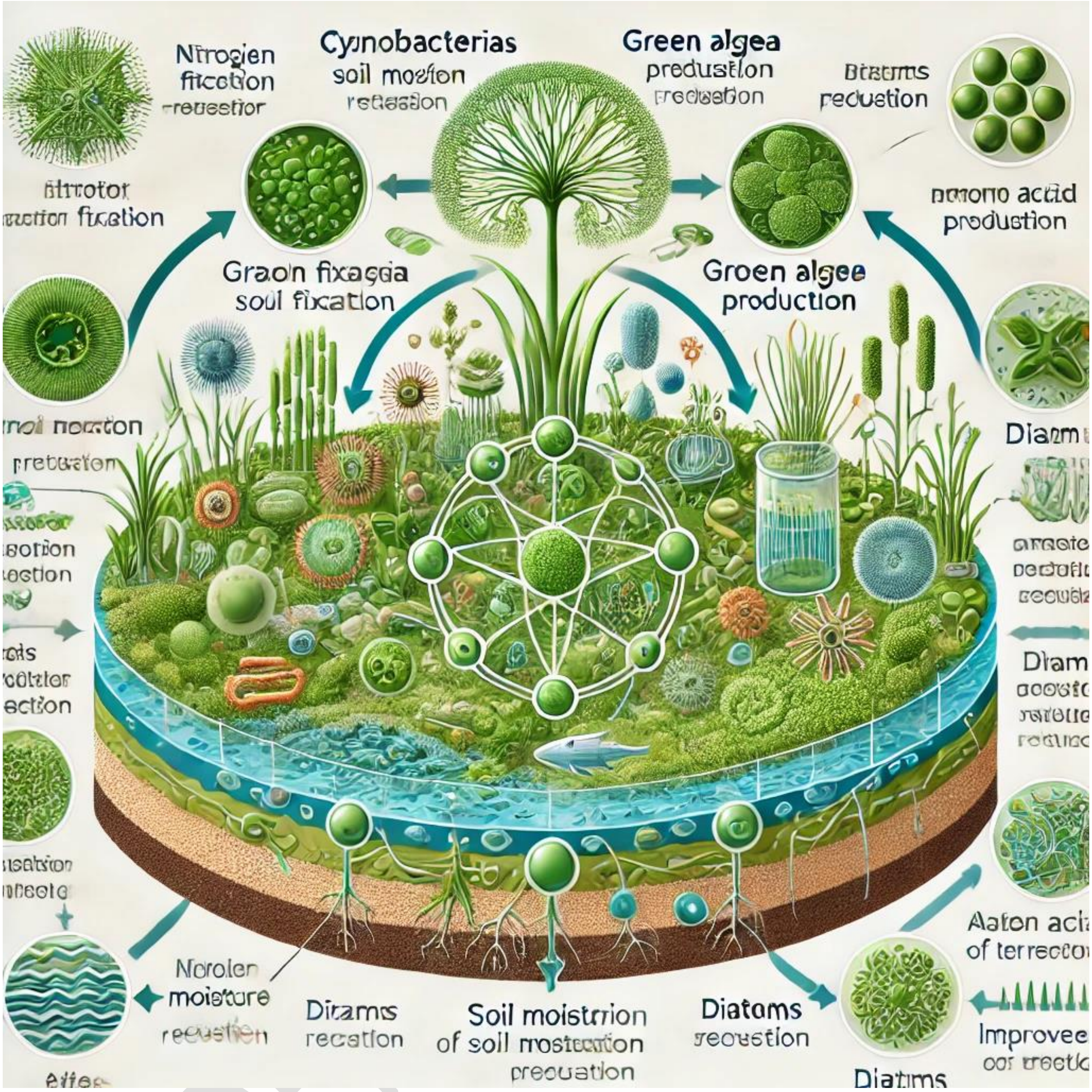

Figure 1: Scientific diagram showing the composition and mechanisms of an algal consortium as a biofertilizer, including the roles of Cyanobacteria, Green Algae, and Diatoms. The connections highlight the nutrient cycling, soil improvement, and biocontrol benefits that enhance soil fertility and plant growth.

These species work in synergy to enhance soil fertility, nutrient availability, and plant growth. Algal consortia also produce extracellular polysaccharides, which help improve soil texture and support beneficial microorganisms.

Mechanisms of Algal Consortia in Soil Fertility Enhancement

1. **Nutrient Enrichment**: Algal consortia can convert atmospheric nitrogen and phosphorus into bioavailable forms. Additionally, they release potassium and trace elements essential for plant growth.
2. **Soil Structure Improvement**: Algal biofilms in the soil form polysaccharides that improve soil aggregation, thereby enhancing water retention and aeration. This improves root penetration and nutrient uptake by plants.
3. **Microbial Activity Stimulation**: Algae secrete compounds that support soil microbial communities, enhancing soil fertility and promoting the growth of beneficial bacteria and fungi.
4. **Phytohormone Production**: Algal consortia produce natural plant hormones, which enhance root development, shoot growth, and overall plant vigor.
5. **Heavy Metal and Pathogen Control**: Algae can bind and immobilize heavy metals, reducing their uptake by plants and thus acting as a bioremediation tool. Additionally, they exhibit antifungal and antibacterial properties, reducing disease incidence in crops (Carvajal-Muñoz & Carmona-Garcia, 2012).

Comparative Analysis: Algal Consortium vs. Chemical Fertilizers

Chemical fertilizers have long been used to achieve high crop yields, but they often have deleterious effects on soil and environmental health. In contrast, an algal consortium-based biofertilizer offers the following advantages:

- **Sustainability**: Algal biofertilizers are renewable and biodegradable, reducing dependency on non-renewable resources and synthetic inputs.
- **Soil Health**: Unlike chemical fertilizers, algal biofertilizers improve soil organic matter and promote beneficial microbial activity, resulting in better long-term soil fertility.
- **Reduced Pollution**: Algal biofertilizers minimize nutrient leaching and prevent groundwater contamination, unlike synthetic fertilizers, which contribute to eutrophication.
- **Lower Input Requirement**: Algal biofertilizers may reduce the need for additional chemical inputs, as they provide multiple benefits (fertilization, biocontrol, bioremediation) simultaneously.

Table:1 Effectiveness and Sustainability of Algal Fertilizer with Chemical Fertilizer

Aspect	**Chemical Fertilizers**	**Algal Consortium Biofertilizers**

Nutrient Enrichment	Provides targeted nutrients but often leads to nutrient leaching	Enhances nitrogen fixation, phosphorus solubilization, and potassium availability naturally
Environmental Impact	Contributes to water pollution and soil degradation	Eco-friendly and biodegradable; reduces environmental contamination
Soil Health	Long-term use degrades soil organic matter	Improves soil structure, moisture retention, and microbial diversity
Plant Growth Promotion	Limited by high salinity and acidity of chemical inputs	Produces natural growth-promoting phytohormones like auxins, gibberellins, and cytokinins
Microbial Community Impact	Can reduce beneficial microbial populations	Supports beneficial microorganisms, promoting soil biodiversity
Heavy Metal and Pathogen Control	May contribute to heavy metal buildup	Algal bioremediation properties help immobilize heavy metals and suppress pathogens
Economic Feasibility	High initial efficiency but environmentally costly over time	Generally higher initial costs, with long-term sustainable benefits
Climate Adaptability	Limited; often requires specific application conditions	Versatile in diverse climates and adaptable to various soil types
Biocontrol Potential	Minimal natural pest control, often necessitating pesticide use	Exhibits antifungal and antibacterial properties, reducing reliance on pesticides
Sustainability	Non-renewable and environmentally taxing	Renewable and sustainable, reducing dependence on fossil-fuel-derived inputs

Field Applications and Case Studies

Several field studies and trials have demonstrated the effectiveness of algal consortium biofertilizers:

Application of Liquid consortium on *Solanum melongena* plant:

10-15 days old crop were collected from the nursery and sapling of plants in pot. Uniform size plants were selected for the sapling. 9 pots were taken for the pot study. Consortium of prepared algal biofertilizer were applied after 15 days of planting. 7 different algal consortia were applied for the different plant one pot taken as chemical fertilizer and one pot remains untreated as control. Following treatment were applied to brinjal plant: B0: Control, B1: Chemical fertilizer, B2: *Chlorella* + *Chlamydomonas*, B3: *Chlorococcum* + *Gloeocapsa,* B4: *Chlorococcum* + *Chlorella,* B5: *Chlorococcum* + *Chamydomonas,* B6: *Scenedesmus* + *Gloeocapsa,* B7: *Scenedesmus* + *Chlorella,* B8: *Chlorococcum* + *Chamydomonas*

Plant growth parameter:

Table 2: Measurement of plant growth parameter at different days

Treatments	**Plant height (cm)**			**Plant width (cm)**			**Number of leaves/ plant**		
	30 days	**60 days**	**90 days**	**30 days**	**60 days**	**90 days**	**30 days**	**60 days**	**90 days**
B0	22	33	37	70	110	115	16	18	22
B1	21	28	30	62	95	102	11	9	12
B2	20	33	34	67	97	99	10	9	15
B3	19	23	26	50	92	98	5	8	17
B4	20	30	35	65	105	112	9	20	25
B5	24	36	40	72	115	125	17	19	27
B6	24	29	32	75	117	123	18	22	27
B7	20	29	34	65	107	115	10	16	33
B8	19	37	43	57	102	113	7	14	32

Throughout the experiment, plant growth parameters treated with various algal consortia were compared to a control. At day 30, plants treated with B5 and B6 exhibited significantly greater height than the control, a trend that continued through day 60, with B5 and B8 leading to taller plants. By day 90, B5 and B8 achieved the maximum plant height, indicating their effectiveness in promoting height growth throughout the experimental period.

In terms of plant width, treatments B5 and B6 showed the widest growth from day 30 onwards, consistently outperforming the control at all stages up to day 90. This suggests B5 and B6 were particularly effective in promoting broad, healthy growth.

Regarding the number of leaves, plants treated with B5 and B6 had the highest leaf counts at days 30 and 60, stimulating early leaf production. By day 90, B5, B6, B7, and B8 all contributed to higher leaf production compared to the control, with B8 also demonstrating significant benefits in height and leaf production.

In summary, B5 and B6 consistently provided superior results in plant height, width, and leaf number through the first 60 days, while B8 showed promising results in height and leaf production by day 90.

Nutrient content measurement from soil:

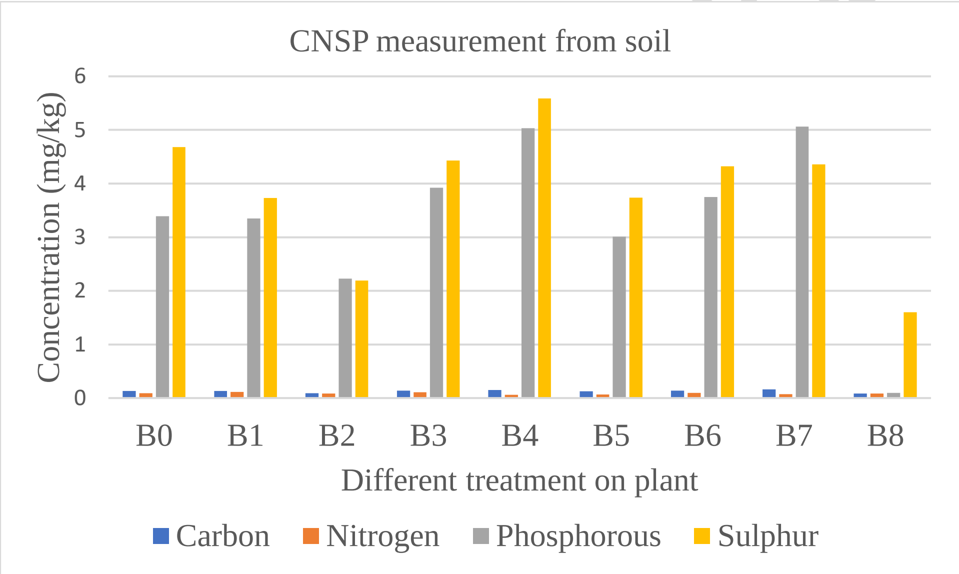

Figure 2: CNSP measurement from soil after application of biofertilizer

Study of Carbon, Nitrogen, Sulphur and Phosphorous content of soil from *Solanum melongena* (Alef, K., & Nannipieri, P., 1995). Carbon content was higher in B3, B4, B6, and B7 compared to the control (B0), indicating a higher accumulation of carbon in these treatments.

Nitrogen content was elevated in all treatments except B4 and B7 when compared to the control, suggesting a general increase in nitrogen levels across most treatments.

Phosphorous content was higher in B1, B3, B4, B6, and B7 relative to the control, indicating increased phosphorus levels in these treatments.

Sulphur content was notably higher in B4 compared to the control, indicating an increase in sulphur in this treatment.

Chlorophyll measurement:

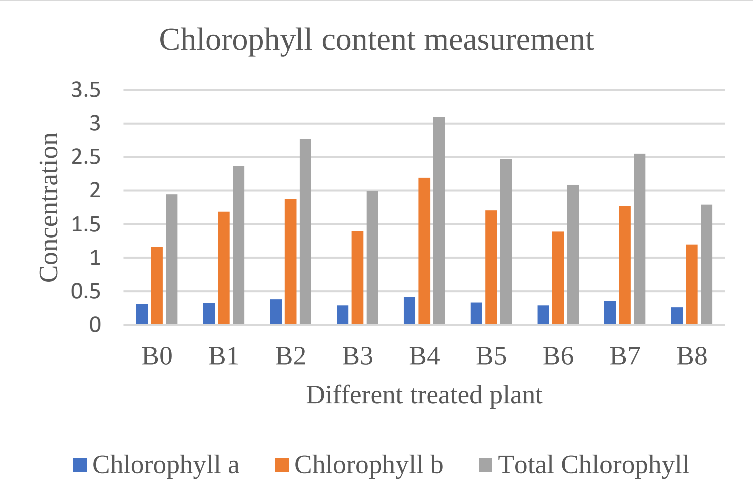

Figure 3: Chlorophyll content estimation from brinjal plant

Chlorophyll a, chlorophyll b, and total chlorophyll content (Parry *et al.,* 2014) were significantly higher in brinjal plants treated with B2, B4, B5, and B7 compared to both the control and the chemical fertilizer-treated plants. This suggests that these treatments were more effective in promoting chlorophyll synthesis, which is essential for photosynthesis, compared to the conventional chemical fertilizer. The increased chlorophyll content in B2, B4, B5, and B7-treated plants likely contributed to better overall plant health and growth, as higher chlorophyll levels typically indicate enhanced photosynthetic efficiency and improved nutrient uptake.

Plant growth hormone analysis:

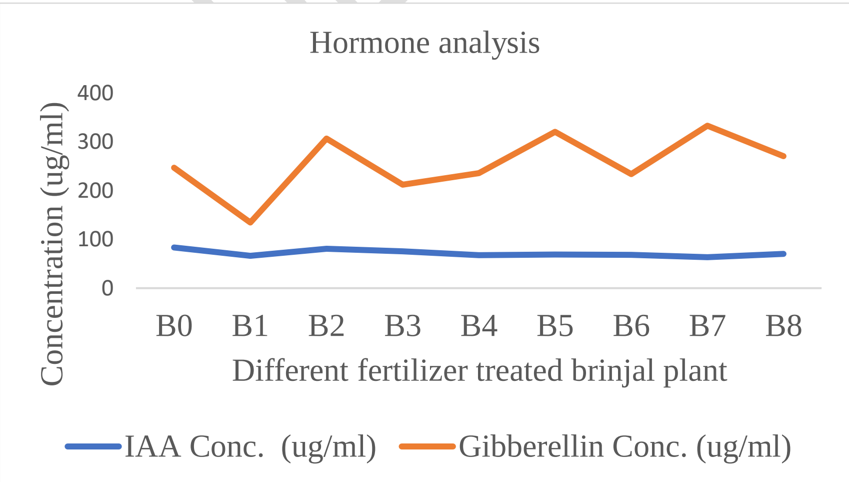

Figure 4: Hormone analysis of Brinjal plant

Plant hormone IAA concentration was analyzed by using method Gordon & Weber (1951) and Gibberellin were measured by using Graham & Henderson (1961). The analysis of key plant growth hormones, IAA (Indole-3-acetic acid) and Gibberellin, revealed notable differences between treatments. Control plants had the highest IAA concentration, indicating naturally higher IAA production without treatment. However, plants treated with algal biofertilizers (B2, B4, B5, and B7) showed significantly increased IAA levels compared to those treated with chemical fertilizers, suggesting these biofertilizers effectively enhanced IAA production, promoting better root development and overall growth.

For Gibberellin, plants treated with B2, B5, and B7 exhibited higher concentrations than the control, indicating these treatments effectively boosted gibberellin levels. Gibberellin promotes stem elongation and overall growth, and its levels were consistently higher in algal biofertilizer-treated plants compared to those treated with chemical fertilizers, highlighting the superior potential of algal biofertilizers in hormone regulation.

Applications of Solid consortium

Preparation of immobilized algal bead:

3 g Algal biomass was mixed with 100ml 3% Sodium alginate. The above mixture was poured into a syringe and added dropwise to a cold 0.7% $CaCl_2$ solution. Beads were transferred in 0.7% $CaCl_2$ solution and stored for 2 hours at 4 ^{0}C. Beads were washed with 0.2M phosphate buffer (pH-7) (Da Costa *et al.,*1991; Soares *et al.,*2022). The beads were stored at 4 ^{0}C for further analysis. The beads were coated with chitosan. All algae beads were dried in sun and stored for later analysis.

Application of immobilized beads on Brinjal plant: 8-10 days old crop were collected from the nursery and sapling of plants in pot. Uniform size plants were selected for the sapling. 12 pots were taken for the pot study. Consortium of prepared algal beads were applied after 15 days of planting. 10 different algal consortium beads were applied for the different plant one pot taken as chemical fertilizer and one pot remains untreated as control. Following treatment were applied to brinjal plant: A0: Control, A1: Chemical fertilizer, A2: *Chlorococcum* + *Scenedesmus*, A3: *Chlorococcum* + *Gloeocapsa,* A4: *Chlorococcum* + *Chlorella,* A5: *Chlorococcum* + *Chlamydomonas,* A6: *Scenedesmus* + *Gloeocapsa,* A7: *Scenedesmus* + *Chlorella,* A8: *Scenedesmus* + *Chlamydomonas,* A9: *Gloeocapsa* + *Chlorella,* A10: *Gloeocapsa* + *Chlamydomonas* and A11: *Chlorella* + *Chlamydomonas.*

Plant growth parameter:

Measured plant height in centimeters (cm) from the base of the stem to the top of the canopy, or the highest part of the plant. Width is distance from front to back. And also measured number of leaves present per plant.

Table 3: Measurement of plant growth parameter at different days

Treatments	**Plant height (cm)**			**Plant width (cm)**			**Number of leaves/ plant**		
	30 days	**60 days**	**90 days**	**30 days**	**60 days**	**90 days**	**30 days**	**60 days**	**90 days**
A0	22	25	27	35	115	119	4	16	30
A1	21	22	22	25	120	135	3	28	56
A2	14	20	21	40	107	112	3	11	17
A3	20	30	34	42	108	118	2	15	22
A4	20	25	25	23	97	106	8	14	17
A5	21	26	28	45	102	111	4	13	17
A6	20	27	30	43	115	127	7	15	22
A7	21	25	27	41	105	112	4	10	27
A8	17	27	32	38	103	105	2	8	25
A9	21	20	25	42	118	130	7	24	35
A10	17	26	28	40	106	109	3	10	25
A11	19	26	30	42	106	115	6	21	26

At the harvesting stage, notable differences in plant growth metrics were observed among various treatments compared to the control group. Specifically, plant height significantly increased with treatments A3, A5, A6, A7, A8, A10 and A11 indicating these treatments were more effective in promoting vertical growth than the control.

Plant width, measuring lateral expansion, was significantly greater in treatments A1, A6, and A9 compared to the control, suggesting these treatments had a beneficial effect on the plants' overall spread.

Additionally, the number of leaves, a critical parameter indicating plant health and photosynthetic capacity, showed significant improvement with treatments A1, A7, A8, A9, A10, and A11, resulting in a higher leaf count compared to the control.

Overall, these observations highlight the positive impact of certain treatments on plant height, width, and leaf number, suggesting specific combinations or types of treatments can significantly enhance plant development compared to control conditions.

Nutrient content measurement from soil of brinjal plant:

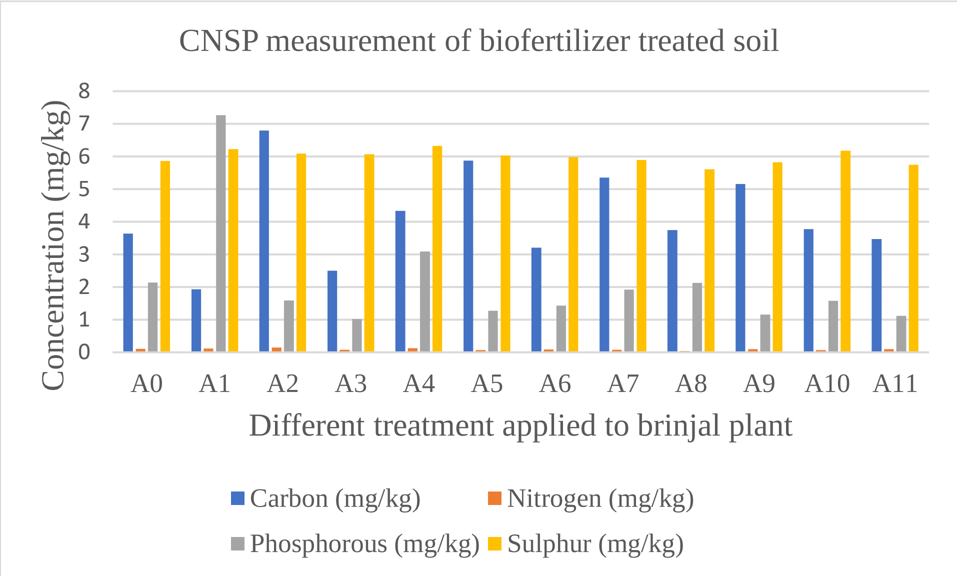

Figure 5: CNSP measurement from soil of brinjal plant after application of biofertilizer

Study of Carbon, Nitrogen, Sulphur and Phosphorous content of soil from *Solanum melongena* (Alef, K., & Nannipieri, P., 1995). The analysis of soil nutrient content shows that different treatments impact brinjal plant nutrient levels in distinct ways. Immobilized beads significantly increased soil carbon content, enhancing fertility and plant growth. Nitrogen levels were notably higher in plants treated with A2 and A4 beads, boosting nitrogen availability crucial for protein synthesis and plant health. Chemical fertilizers resulted in the highest phosphorous content, providing essential nutrients in higher concentrations. Sulphur content was significantly elevated in soils treated with A4 beads, highlighting their unique benefit in enhancing sulphur availability for plant metabolic processes. Overall, immobilized beads effectively improve carbon and nitrogen levels, chemical fertilizers are more efficient for phosphorous, and A4 beads are particularly beneficial for sulphur enrichment, demonstrating the varied efficacy of these treatments in meeting specific soil nutrient needs.

Chlorophyll content measurement

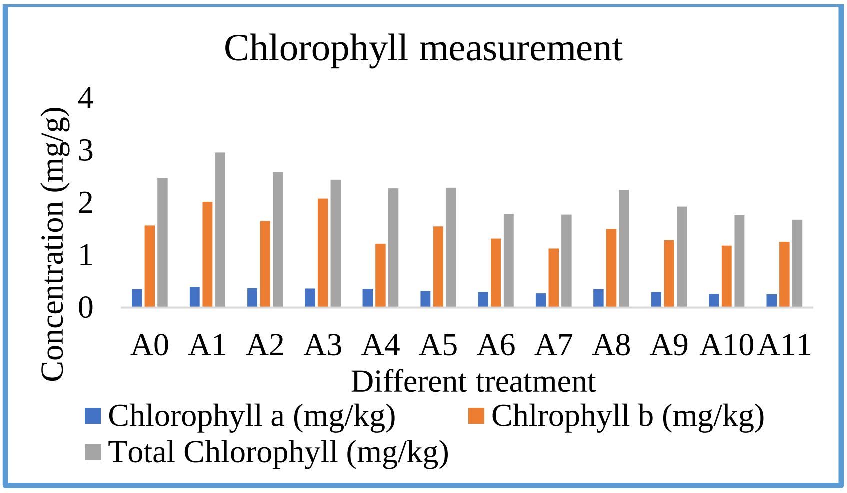

Figure 6: Chlorophyll measurement from Brinjal plant

Chlorophyll content was measured in the leaves of brinjal plants at the flowering stage, assessing Chlorophyll a, Chlorophyll b, and total chlorophyll content (Parry *et al.,* 2014). Treatment A1 resulted in the highest Chlorophyll a content, while A2 had the highest Chlorophyll b content. Overall, A1-treated plants exhibited the highest total chlorophyll content compared to the control.

A1 treatment effectively enhanced Chlorophyll a level, crucial for capturing light energy during photosynthesis. A2 treatment increased Chlorophyll b content, broadening the light absorption spectrum and improving light energy capture.

Plant hormones:

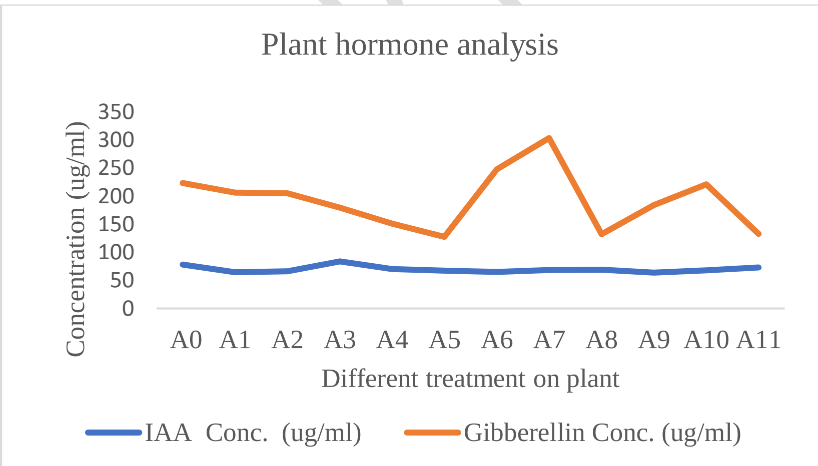

Figure 7: Hormone analysis from brinjal plant

IAA concentration (Gordon & Weber, 1951). were higher in all algal biofertilizer treated plant as compared to Chemical fertilizer treated plant and control plant whereas, Gibberellin concentration (Graham & Henderson, 1961) was maximum in A6 and A7 treated plant as compared to chemical fertilizer treated plant and control plant.

These examples highlight the potential of algal consortia in diverse climatic conditions and crop systems, proving their adaptability and effectiveness in real-world agricultural scenarios.

Challenges and Limitations

While promising, algal consortium biofertilizers face certain challenges:

1. **Cultivation and Scaling**: Large-scale production of algal consortia requires specific conditions, including controlled light, temperature, and nutrients, which can be cost-intensive.
2. **Storage and Application**: Algal biofertilizers are sensitive to environmental conditions, making their storage and transportation challenging. Proper application methods must also be developed to maximize their efficacy.
3. **Field Variability**: Algal biofertilizers may perform inconsistently in different soils and climates, necessitating further research to understand and optimize their effects under various field conditions.
4. **Economic Viability**: The initial costs of producing algal consortia may be higher than traditional fertilizers, which may deter some farmers, especially in developing regions, from adopting them without incentives or subsidies.

Future Prospects and Research Directions

Research on algal consortium biofertilizers is still in its early stages, and several areas warrant further investigation:

1. **Optimization of Consortia Composition**: Understanding the optimal mix of algal species and their ratios for various crops can enhance biofertilizer performance.
2. **Field Trials in Diverse Environments**: Conducting trials in diverse climatic and soil conditions will help adapt algal biofertilizers to different agricultural systems.
3. **Cost-Effective Production Methods**: Developing efficient, large-scale cultivation methods could make algal biofertilizers more affordable and accessible.
4. **Integrated Pest and Disease Management**: Exploring the biocontrol potential of algal consortia could contribute to holistic, eco-friendly farming practices that minimize the need for pesticides.

Conclusion

The soil should be fertile enough to give high production and plants require critical nutrients from fertile soil which also supports a diversified and dynamic biotic population that helps the soil resist environmental degradation. Bio fertilization is a sustainable agricultural practice that includes using bio-fertilizer to upsurge the nutrient content of the soil and organic matters, resulting in higher productivity. Micro and Macro algae are correct environmentally friendly bio-based fertilizers for pollution-free agricultural applies. Microalgae are more effective bio-fertilizers to soil than macroalga, but macro alga gives the best results in mega scaled aquatic media in addition to the availability for the reproduction of huge bulk from microalga rapidly in the laboratory. Microalga recorded the utmost levels of soil fertility with clay soil than a sandy one. Both micro and macro alga can be used for heavy metal removal similarly. Algal consortium-based biofertilizers offer an innovative approach to sustainable agriculture, providing a natural means of enhancing soil fertility, improving plant growth, and reducing environmental impact. Through their unique ability to work synergistically, different algae species contribute to the overall health and productivity of the soil ecosystem. Although challenges remain in production and application, the potential benefits of algal biofertilizers make them a promising alternative to conventional synthetic fertilizers. Continued research and development, along with supportive agricultural policies, can help promote the adoption of algal consortia as a viable solution for sustainable food production and environmental conservation.

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