Plant Archives Vol. 25, Special Issue (ICTPAIRS-JAU, Junagadh) Jan. 2025 pp. 430-432
e-ISSN:2581-6063 (online), ISSN:0972-5210

Plant Archives

Journal homepage: http://www.plantarchives.org
DOI Url : https://doi.org/10.51470/PLANTARCHIVES.2025.SP.ICTPAIRS-062

INTEGRATING ADVANCED TECHNOLOGIES AND SUSTAINABLE PRACTICES FOR ENHANCED SOIL HEALTH MANAGEMENT AND PLANT NUTRIENT OPTIMIZATION

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ABSTRACT

The management of soil health and plant nutrient optimization is pivotal for achieving sustainable agriculture and ensuring global food security, particularly in the face of climate change and increasing food demand. Integrating modern soil testing protocols, such as spectroscopic analysis and high-throughput screening, enables the accurate quantification of nutrient profiles and the early detection of nutrient imbalances. These technologies make it possible to check important soil parameters in real time, such as nutrient levels, organic matter, and microbial activity. This helps farmers make decisions based on data and gives them useful information for acting quickly and getting better nutrient use. Modern soil testing methods, combined with strategies like slow-release fertilizers, foliar applications and nutrient management planning, are crucial for minimizing nutrient runoff and losses while enhancing nutrient efficiency. Organic farming practices, including crop rotation, cover cropping, and the application of organic amendments along with bio-fertilizers, are important for enhancing soil organic carbon sequestration, improving water retention, and stimulating beneficial microbial communities. Educational outreach and extension services play a critical role in disseminating these sustainable practices, empowering farmers with the knowledge needed for effective soil and nutrient management. This review emphasizes the need for a holistic approach that integrates technology, education, and sustainable practices to achieve optimized soil health management and plant nutrient use. The study presented in the paper highlights the ways to improve the seed germination process by identifying and establishing the application of hydrogel in agriculture, which is economic, non-toxic and eco-friendly. Hence, the further focus of this research will be establishing a process of synthesizing bio-based hydrogels in the laboratory and their application in the field by working on the technique of slow-releasing fertilizers from hydrogels and their effect on crops for better growth and production.

Key words : Plant nutrient optimization, Precision agriculture, Soil health management, Sustainable agriculture, Soil-testing protocols.

Introduction

With millions of people's livelihoods shaped by it and a major GDP contribution, agriculture is the backbone of the Indian economy and society. For most people in India, it's a way of life rather than merely an economic endeavour. Over half of the workforce in the nation works in this field, which also supplies vital raw materials to other industries. The agricultural sector is essential to guaranteeing food security and nutrition for India's enormous population because of the country's various agro-climatic conditions, which supports a large range of crops and livestock. Agriculture has a significant cultural and social significance in India, as seen by the numerous festivals, customs, and daily rituals that revolve around its cycles. Moreover, agriculture has a significant impact on rural development and the socioeconomic standing of the region.

The increasing global population and the challenges posed by climate change necessitate a paradigm shift in agricultural practices to ensure food security and environmental sustainability. Traditional farming methods, often reliant on synthetic fertilizers and extensive tillage have led to soil degradation, reduced biodiversity and increased greenhouse gas emissions. In contrast, modern approaches emphasize the integration of technological advancements with sustainable practices to restore and maintain soil health while optimizing plant nutrient use (Lal, 2020).

Modern soil testing methods, such as spectroscopic analysis and high-throughput screening have revolutionized the way soil health is assessed. These technologies offer precise quantification of soil nutrient profiles and enable early detection of nutrient imbalances, allowing for timely and targeted interventions. Spectroscopic techniques provide rapid and non-destructive analysis of soil components, facilitating real-time monitoring of critical soil parameters such as nutrient levels, organic matter content and microbial activity (Haug *et al.*, 2017; Shepherd and Walsh, 2017). High-throughput screening, on the other hand, enables the processing of large soil samples quickly, thereby enhancing the efficiency of soil analysis (Gomez *et al.*, 2021).

Along with advanced analytical techniques, the development of innovative materials such as hydrogels has significantly enhanced the efficacy of slow-release fertilizers. Hydrogels are cross-linked polymer networks capable of absorbing and retaining large quantities of water and nutrients. When used in slow-release fertilizers, hydrogels regulate the release of nutrients over an extended period, reducing nutrient leaching and improving nutrient use efficiency (Yuan *et al.*, 2019). The controlled release mechanism of hydrogels ensures that nutrients are available to plants as needed, thereby minimizing environmental impact and optimizing plant growth. The integration of hydrogels into fertilizer formulations aligns with the principles of precision agriculture by providing a sustainable solution to nutrient management challenges. Based on these facts, a study was conducted to demonstrate the significance of hydrogel for plants.

Materials and Methods

The study was conducted at Microbiology Laboratory, Anviksha, and GSFC University, in order to standardize best method of introducing fertilizer during seed germination process of Mung Bean. For the study, laboratory synthesized Guar Gum based hydrogels were used. The Mung Seeds were bought from local grocery store and Fertilizer WSF 19-19-19 was sourced from GSFC Limited, Vadodara. Pots were bought from local market and soil was used from the Garden of GSFC University. Tap water was used by spray pump to maintain moisture in pots throughout germination process.

Fig. 1 : Monitoring on 5th day.

Fig. 2 : Monitoring on 7th day.

Table 3 : Pot Trial Study observation data.

Treatment	Germination percentage	Germination count	Root length (cm)	Shoot length (cm)	Total seedling length (cm)
Absolute Control (R_1)	30%	3 out of 10 seeds	1 cm	5.5 cm	6.5 cm
Fertilizer-Loaded Hydrogel (R_1T_3)	70%	7 out of 10 seeds	1.5 cm	9 cm	10.5 cm

Table 4 : Pot Trial study results.

Treatment	Vigour Index (%)	Germination observation	Reason for No Germination
Absolute Control (R_1)	193%	Moderate germination (3 out of 10 seeds)	-
Fertilizer-Loaded Hydrogel (R_1T_3)	735%	Higher germination (7 out of 10 seeds)	-
Plain Hydrogel (R_1T_1)	-	No significant germination	Soil hardened
Only Fertilizers (R_1T_2)	-	No significant germination	Soil hardened

Table 1 : Requirement of Hydrogels based on soils.

Type of soil	Suggested dosage of Hydrogel
Arid & Semi-arid Regions	4-6 g/kg soil
For all levels of water stress treatment and improved irrigation	2.25-3 g/kg soil
To delay permanent wilting point in sandy soils	0.2-0.4 g/kg OR 0.8% of soil, whichever is more
To reduce irrigation water by 50% in loamy soil	2-4 g/plant pit
To improve relative water content and leaf water use efficiency	0.5-2.0 g/pot
To reduce drought stress	0.2-0.4% of soil

Table 2 : Sizes & Quantities of the material used in the study.

Pot Size (Lit)	Pot Diameter (Top) cm	Pot Diameter (Bottom) cn	Pot height cm	Amount of Soil (Kg)	No. of seeds	Amount of Hydrogel	Amount of Fertilizer
2 lit	17	12	13	1.5 approx.	10 in each pot	5g	2.5 g

Method

Absolute Control and three treatments of seed germination in two replications *viz*., Absolute Control (R_1 & R_2), with plain hydrogels (R_1T_1 & R_2T_1), with only fertilizer (R_1T_2 & R_2T_2), and fertilizer loaded hydrogel (R_1T_3 & R_2T_3) were set up and evaluated by screening a range parameter at various duration (Where, R= Replication & T = Treatment). For entire study, in each treatment same size of pot, equal amount of soil, measured quantity of hydrogels and fertilizers were used. The experiment was carried out in replication to validate the results.

Results and Discussion

Based on pot trial observations following outcomes were drawn as mentioned in the Table 3.

Seed vigour index and seed vigour mass are calculated using germination percentage and seedling length. The vigour index indicates the overall effect of fertilizers and hydrogels on quality parameters of seeds. Seed Vigour index is calculated using formula 1:

$$\text{Seed Vigour Index (SVI)} = \text{germination (\%)} \times \text{seedling length} \quad (1)$$

The details of vigour index and other observations are mentioned in Table 4.

It was found that all the treatments for seed germination showed significant differences with the control and the highest germination %, seedling length, weight and vigour index were observed in treatment with fertilizer loaded hydrogels ($R_1T_{3)}$.

Conclusion

Fertilizer loaded hydrogel crystals can be a revolutionary change in next generation farming because its application increases productivity in almost all the test crops (cereals, vegetables, oilseeds, flowers, spices, etc.) in terms of crop yield. It also helps improve the quality of agricultural produce in terms of plant biomass, fruit and flower size and colour with improvement in hydro-physical and biological environment of the soil. In summary, the integration of advanced technologies, sustainable practices, and effective educational outreach forms the backbone of modern soil health and nutrient management strategies. This holistic approach not only addresses the challenges of food security and environmental sustainability but also paves the way for a more resilient agricultural system capable of adapting to future demands and uncertainties.

Acknowledgement

I express my sincere gratitude to Gujarat State Fertilizers & Chemicals Limited, Vadodara, for enabling my participation in the conference. I also extend my thanks to GSFC University, Vadodara, for supporting this research, and to my guides, Dr. Santhosh Kumar and Dr. Pujan Vaishnav, for their invaluable mentorship. Special thanks to Mr. Rushabh Shah and Mr. Vaidik Adhyaru for their contributions. I am deeply grateful to Mr. Manish Raval, Mr. Sandip Rajguru and Mr. Gaurang Kelaiya from the Soil & Water Testing Laboratory, GSFC and to the staff at Anviksha, GSFC University, for their unwavering support.

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