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Technology Innovation: A Green Approach to Soil Health

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This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Soil is a critical factor in determining plant growth and development. With approximately 30% of Indian soils degraded, caused by excessive fertilizer use, monocropping, and climate change such as cyclones, floods, cloudbursts, and landslides, the nation faces a crucial task of reversing soil damage. Thus this paper, highlights the importance and the utility of diversifying nutrients through different organic manure production techniques (fermentation/ decomposition or composting process), use of mountain micro-organisms, weed manures, crop residues, oil cakes and bio-fertilizers. These organic sources not only improve soil fertility and soil productivity but also

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replenishes soil with nutrients. Additionally, practices like conservation tillage has a huge scope to reduce soil compaction and improves soil structure. Smart innovations including, soil remediation, bio inoculation of extremophiles, high-quality worm castings free of chemical additives, and genetically-modified organisms (GMOs) can be harassed and used effectively to reduce use of commercial fertilizers. Under rapid progressing water deficits and climate change, use of hydrogels and cultivation of Fonio, a nutritious gluten-free grain can serve as an alternative to combat drought and retain water. The potential of new innovative technology along with precision agriculture and A. I can aid soil health. Low-cost technology, coupled with a reliable mobile app that provides AI-based agricultural information and collaboration with various agencies, can significantly boost the economy of small-scale farmers. It can reduce crop health issues, minimize post-harvest losses, improve farmers' income, enhance resource use efficiency, and promote balanced nutrient application, which in turn can help to mitigate the diverse effects on soil.

Keywords: Soil health, organic practices; technology innovation; precision agriculture; A.I.

1. INTRODUCTION

Fertile soil is a critical factor in determining plant growth and development. Soil health is not only confined to the wellbeing of plants but the overall growth of microorganisms and the functionality of soil as a living ecosystem. The decrease in nutrient use efficiency as well as agricultural productivity is a direct results of deteriorating soil health. Nutrient mining is another term used to indicate the negative balance between nutrient addition and nutrient removed by crops.Indian soils during 2017-18 showed a negative balance of 8 to 10 million tons per year (NAAS, 2018), therefor maintaining soil in optimum health is a pre-requisite to support necessary food grain production and sustain ecological services (Katyal et al., 2016).

“According to the National Bureau of Soil Survey and Land Use Planning, around 30% of the soil in India is degraded” (ICAR-NBSS&LUP. 2021).

“This gains further importance, since recent estimates show a loss of 24 billion tons of fertile soil every year, an alarming trend that could have more than 90% of Earth’s land area degraded by 2050” (Gomiero, 2016). Excessive ploughing, planting the same crop year after year and excessive fertilizer use impacts approximately 33% of the planet's land area (FAO and ITPS 2015). Some of the unintended consequences include soil acidification (Marris, 2022), nutrient imbalance (Zhang et al., 2015), negative impacts on soil biota (Strecker et al., 2021), and soil pollutions (Zhang et al., 2015, Gu et al., 2023). Many anthropogenic activities have added threats to the health of soil ecosystems, leading to the loss of biodiversity (Estrada-Carmona et al., 2022), decline in organic matter (Lal, 2020), and irreversible salinization (Hassani et al., 2021). About 70% of soils suffer either from soil acidity (22.9%) or alkalinity (41%), Water logging causes salinization (Saline 32%) and damages soil, resulting in an annual loss of 1.2 to 6.0 m tonnes of grains. (Reddy, 2023. National Soil Health Card (SHC)).

“Over six decades of green revolution, the use of fertilizer nutrients has increased from 0.30 Mt in 1960-61 to 32.54 Mt in 2020-21”. (Das et al, 2022). The effect of fertilizers pesticides, fossil fuel energy, accumulation of toxic compounds (Agrochermicals) coupled with intensive tillage and mono-cropping has had a negative impact on soil health. National Soil Health Card (SHC) mission revealed the deteriorating health of Indian soil, ie., primary nutrients was found deficient at 96% for N, 61% for P, and 62% for K and about 52.1% in organic carbon. (Khurana and Kumar, 2022). Deficiencies of more than one micronutrient along with primary soil nutrients have also been reported at several locations in the country. There are deficiencies of micronutrients like Iron (25.8%), Zinc (35.5%) Boron (18.1%), Manganese (14.6%). “Thus, both primary and micronutrient deficiencies have now become the major constraint in sustaining high crop yields in present-day intensive agriculture across India” (Das et al, 2022). Climate change has further exacerbated soil health. Due to rapid progressing water deficits and climate change, results of improper soils use has worsened (Baghbanzadeh et al., 2017). “According to a report, India lost approximately 5.04 million hectares of crop area due to cyclones, floods, cloudbursts, and landslides” (Mahapatra, 2022).
To address these challenges, proper farming strategy with smart innovations, Sustainable soil practices, can help alleviate the use of excessive mineral fertilisers/ agrochemicals. “Building soil

fertility through the use of natural soil additives and organic manures, using water resources efficiently, and properly managing waste, are designed to combat soil degradation, support formation, and soil health". (Buzzard et al., 2021; Sharma et al., 2022).

"Startups and scaleups are also developing technological solutions with a sustainable approach with an aim to mitigate soil stress and improve agricultural productivity. Technology innovation have greatly shaped agriculture throughout time. From creation of plough to Global positioning system (GPS) resulting in more efficient use of resources and soil management. Agricultural technology along with organic farming with emphasis on soil health needs to be explored to enhance utilization of resources without exploiting the environment more than it has already been" (Anonymous, 2024).

2. UNLOCKING AGRICULTURAL SUSTAINABILITY THROUGH ORGANIC PRACTICES AND SMART INNOVATION TECHNOLOGY

2.1 Diversifying Nutrient Sources

Monotonous excessive use of chemical fertilizer can result in soil and water pollution, negatively impacting not only crops but the ecosystem and human health as well. The imbalance use of these fertilizers and lack of attention for fertilization of secondary nutrients, such as sulfur, and micronutrients, viz. Fe and Zn, lead to their widespread deficiency (Tandon, 2013). Use of only one nutrient source cannot fulfil the demand of crop as well as the soil, therefor nutrients of different sources should be incorporated. Different nutrient sources through agro industrial wastes, minerals (without processing), green and brown manures, weed manures, and bio-fertilizers (Shahane and Shivay, 2021). INM can also improve soil health by integrating organic sources and reducing the use of only chemical inputs. Use of biofertilizers containing beneficial microorganisms can additionally improve soil fertility and soil productivity. These additives not only improve soil structure, health, and resilience by enhancing plant tolerance to salt and drought stress but also provides soil with nutrients such as nitrogen, phosphorus, potassium, essential micronutrients and organic matter. These technologies have been derived naturally or synthetically. "At present, the selection of nutrient source should be such that it provides multiple nutrients for higher yield, has considerable residual effects, and positive influence on soil properties, thereby on soil health and less on environmental footprints". *(*Shahane and Shivay, 2021)

2.2 Organic Manure Production Technique

Liquid fermented organic manure (LFOM): LFOM is the liquid extract obtained during the fermentation or decomposition process. LFOM can be applied directly to the soil or used as a foliar spray.

Practical Utility of Innovation:

1. Beejamrit (mixture of local cow dung, urine, water and lime stirred)
2. Panchagavya (Mixture of 5 kg cow dung, 4 litre urine, 3 litre milk, 2 litre curd, 2 Kg of pulses flour, 1 kg ghee, 2 Kg jaggery and 10 litre water and kept for 15 days)
3. Enriched panchagavya (Cow dung, cow urine, cow milk, curd, jaggery, ghee, banan, tendercoconut water)
4. Amrithakaraisal (Amrit Solution) (Cow dung, cow urine, jaggery)

Fermented organic manure (FOM): These manures are rich in essential nutrients like nitrogen, phosphorus, and potassium. FOM is the solid residue that is obtained after fermentation and decomposition of organic materials

Organic manure is a mixture of plant residues or animal origin viz; FYM, pig manure, poultry manure, goat/ sheep manure, press mud, green manure (sesbania), azolla, city compost; an organic material found in urban solid waste (Pandit et al., 2018).

1. Ghanajeevamritha (solid form of *Jeevmaritha*): Cow dung and urine are mixed with pulse flour, jaggery made into ball like structures and dried under the shade

2.3 Others

Vermi wash: 1 kg adult earthworm devoid of cast resealed in 500 ml Luke warm water (37 to 40 degree C) and agitated for 2 minutes, the released mucus and body fluids collected and mixed for spray.

Compost tea: Fresh compost suspended in barrel for 7 to 14 days
Unseeded weeds and weed clippings + water in 1:10 in a barrel for 3 days.
Egg shell Crushed + water, a rich source of calcium, help prevents blossom end rot in tomatoes.
Crop residues- Rice straw, wheat straw, sorghum stalk, pearl miller stalks
Oil cakes-Castor, cotton seeds, neem, sunflower, neem, linseed
"Biofertilizers- are ready to use live formulates of beneficial microorganisms that on application to seed, root or soil mobilize nutrients through their biological activity in particular, and help in building up the micro-flora and soil health in general. It includes, blue green algae (BGA), rhizobium, azotobacter, azospirillum, phosphate solubilising and mobilising bio inoculants (PSB) and plant growth promoting rhizobacteria (PGPR)". (Kumar et al., 2022).

2.4 Mountain Microorganisms

A collection of various beneficial microorganisms found in virgin soils or forest decomposing organic matter. It can be used in the preparation of solid and liquid organic fertilizers. They can also be applied directly on the plant leaves to control certain pests and diseases or as a growth booster.

Practical utility of innovation:

1. decomposing forest leaves (debris) + 10 kg of rice/wheat or maize bran+ 1 litres of molasses + 3 litres of clean water (not contaminated)
2. Bokashi- 1 sack of chicken manure, 1/2 sack of charcoal or carbon dust, 1 sack of saw dust, 2 litres of molasses, 2 litres of activated mountain micro-organism solution, 1 sack of rice or coffee husks, 1/2 sack of chopped green grasses and banana stems, 2 kg of wood ash, 2 kg of fresh cow dung. After mixing and the moisture content is right leave the material in a heap-like structure. On the 15 day after preparation, when it cools, the bokashi fertilizer is stored in gunny sacks and applied during rainy season.
3. Fermented kitchen waste, garden waste, agricultural residues, virgin mountain soils or forest decomposing organic matter
4. Fermented plant juice-Plant juice extracts (weeds, green leafy vegetables), sugar, microbial innoculants.

3. TECHNOLOGY INNOVATION

3.1 Drought Combating

"Hydrogels also known as superabsorbent polymers (SAP), reduces the use of fertilisers, while improving soil properties. SAP are not toxic to plants or the environment" (Marczak et al., 2022). "Hydrogels have also been used in agriculture as soil amendments to improve soil hydraulic properties" (Al-Darby, 1996). "Agriculture, being one of the highest consumers of water, benefits substantially when soil amendments are added to soil to prevent water stress, or for improving soil physical properties. Hydrogels alter soil structure decreasing the number of drainage pores and retaining water. Like soil water infiltration, hydrogel application mostly decreased soil evaporation as soil water is bound to the hydrogel, reducing how much water is lost to the atmosphere. Hydrogels near the soil surface can also increase evaporation by storing water making it easy for stage one of evaporation to occur". (Adjuik et al., 2022). Numerous studies have described the benefits of using SAPs in agriculture and horticulture, where they have contributed to the reduction in water stress, increased yields, and the improvement of biometric parameters (Varela et al., 2016; Yang et al., 2019) and the positive influence of natural soil additives on the availability of soil nutrients (Bhattacharyya et al., 2007; González-Coloma et al., 2022; Kulczycki and Sacała, 2020). "WAGs (water-absorbing geocomposite) are a new type of soil additive with a spatial structure that fully benefits from the sorption capacity of superabsorbent polymers and eliminates some notable limitations. A new biodegradable version of a water-absorbing geocomposite (BioWAG) manufactured from natural animal/plant fibres is one of the few solutions which improves water retention and provides a source of nutrients for plants. The application of waste materials enables an increase in carbon sequestration in the soil and closed-loop fertilisation is an efficient form of recycling". (Marczak et al., 2022).

3.2 Fonio

A deep rooted crop grain grown in Africa cultivated in area with scarce water with high counteract desertification, soil erosion and tolerate harsh environmental conditions. Fonio is a nutritious and gluten-free grain that can be grows on sandy soil without fertilizers or pesticides, providing a high-value and drought-resistant crop.

3.3 Bioinoculants

Bio fungicides and innoculants enhance soil fertility, increase crop yields, reduce fertilizer use, and restore degraded soil affected by salinization or erosion. Ancient microbes known as extremophiles that promote growth under the most extreme conditions when added to soil can be used as seed treatment to significantly increase root mass, length, and density, improving soil health and resistance at the same time. High-quality worm castings free of pesticides, chemical additives, and genetically-modified organisms (GMOs) can be used as an effective alternative to commercial fertilizers

3.4 Soil Remediation & Restoration Practices

Toxic compounds that tend to accumulate due to industrial processes, improper waste disposal excessive use of agrochemicals as fertilizers, plant protection and weed management affect soil health. Some organic sources of crop nutrition, such as sewage and sludge and night soil, are also reported to contain a high amount of heavy metals (Walia and Goyal, 2010; Saha et al., 2018), causing adverse effects on soil health. Utilizing nanoparticles or nanomaterials to target and neutralize contaminants effectively are emerging. Additionally, electrokinetic remediation, harnessing electric currents to decontaminate soil sources, also a promising technology for soil remediation. Rapid removal of contaminants or under immediate threat to soil and human engineered microbes which require less time to degrade the pollutants may be a preferred option. A specially engineered microbes employed to break down contaminants in the soil are becoming an effective way to degrade pollutants and boost soil fertility restoring soil structure and microbial diversity. Startup such as Fixed Earth Innovations: Microbial Marvels for Soil Health, Canadian startup employs specially engineered microbes, the startup offers a tailored solution. The deployment of these microbes is customized on a site-specific basis, providing a targeted approach to restoring soil microbial health. Fixed Earth Innovations addresses a spectrum of contaminants, including hydrocarbons, salinity, sulfolane, and per- and polyfluoroalkyl substances (PFAS), reducing environmental liabilities and promoting sustainable agriculture practices.

3.5 Phytoremediation and Bioremediation

Phytoremediation uses higher plants to rehabilitate soil and groundwater contaminated with metals, pesticides etc. It is environment friendly and cost effective, however it works best when the contamination level is low. It is achieved by phytoextraction (phytoaccumulation), phytovolatilization, Phyto stabilization, or phytodegradation (Yan et al., 2020). Indian mustard (can be used as green manure and weed control), Indian grass- (Gramineae family) remediate petroleum hydrocarbons, Tagetes erecta (Heavy metals like lead, cadmium, copper and chromium), Water hyacinth, Sunflower, Willow tree, etc.

While bioremediation involves use of microbes (namely bacteria, fungi and micro algae) naturally available in the environment to clean the contaminated areas. Certain microorganisms especially bacteria, microalgae and cyanobacteria have the ability to utilize hazardous organic contaminants as sources of their carbon, energy or other nutrients (Megharaj et al., 2014) thereby stimulating their growth. Adding ammendation such as molasses and vegetable oil may improve their growth.

3.6 Soil Compaction Control

Soil compaction is a form of soil degradation as a result of reduced pore space for air and water due to excessive heavy machinery use. The conventional plough tillage involves physical manipulation of soil; therefore, it has several implications on soil health that can be seen primarily on soil physical health, soil biological health, and lastly on soil chemical health (Shahane and Shivay, 2021). A biologically healthy soil is less prone to soil compaction. Soil compaction have several negative effects such as decreased fertility, water infiltration, and inability of soil to supply nutrients to plants, increased soil erosion, Co_2 emission, flooding reduced plant as well as root growth and yield. Conservation tillage improves soil physical and chemical properties, additionally added crop residues are a source of plant nutrient thereby making soil healthy. Conservation tillage system is based on three major principles, viz. continuous or minimal mechanical soil disturbance, maintenance of a permanent biomass soil mulch cover on the ground surface, and diversification of crop species (Kassam et al., 2019) with a combination of fibrous and tap root crops (include forage, cereals, oilseeds and pulses crop) which also creates a deep-rooted channel and add organic matter to the soil (Tiessen, 2010). Conservation Tillage such as No Till i.e., growing crops without soil disturbance, mulch Tillage i.e., soil disturbance but crop residue maintained on the soil. Reduces the intensity of soil tilling or eliminating it altogether to preserve soil structure and reduce erosion.

3.7 Precision Agriculture

Precision agriculture, also known as site-specific farming, combines geospatial data and technology to enable more efficient and targeted soil management. One of the key tools in precision agriculture is the use of geographic information systems (GIS). GIS integrates various data sources such as satellite imagery, soil sample analysis, and weather data. By analysing these maps, farmers can identify variations in soil properties and make informed decisions regarding nutrient application, irrigation, and crop selection. This approach minimizes the risk of overuse or underuse of resources, leading to improved soil health and increased crop yields.

3.8 Application of Artificial Intelligence (A.I)

The integration of AI in food production has led to a 20% reduction in emissions from the agricultural sector labor costs by up to 40%, cut water use by 30% and boost yields, 20% decrease in chemical pesticide usage (Verbitskaya, 2024). The infusion of AI technology in agriculture serves as a valuable tool for controlling and managing unforeseen natural conditions, further fortifying the resilience of the industry. This seamless integration of AI into agriculture marks a significant leap forward, ensuring sustainable and technologically advanced practices in food production (Chaudhari et al., 2024).

A detailed soil maps and use of soil sensors and monitoring devices, measure key soil parameters, including moisture content, temperature, nutrient levels, pH levels. nutrients, organic matter, and microbial activity. This helps to manage land and optimize their soil health and productivity, as well as detect and prevent soil degradation, erosion, nutrient depletion, or contamination. LoT sensors and soil monitoring drones, provide accurate, timely, and affordable soil information, also leveraging of machine learning algorithms and robotics helps to access real-time data on soil quality, leading to more efficient use of resources and higher crop yields.

Map creation using GPS and satellite technology can be an interactive platform for path planning and optimization on-farm activities. A combination of geospatial intelligence and path-planning simulations for machinery use and robots can plan field operations efficiently. After the creation of soil maps, the platform enables farmers to modify and optimize resources to best fit their individual requirements. Remote Sensing with Satellite imagery and drones equipped with AI algorithms can assess soil health and detect issues like erosion or nutrient deficiencies.

Autonomous or semi-autonomous vehicles known as controlled traffic farming (CTF) perform precision farming tasks and GPS-guided equipment, minimize soil compaction caused by heavy machinery, wherein farmers limit heavy machinery traffic to specific lanes within a field, reducing soil compaction. This reduces input costs, soil compaction, and erosion allowing to keep in track of the path the equipment is travelling.

A cable-driven robot covers a farm and performs various farming operations from the sky down using winches on top of masts and cables. It works on any soil type and slope as well as operates automatically according to weather and time conditions. The compaction control robot thus reduces the amount of chemical application needed to grow crops and solve issues of soil compaction, improving crop quality and yield. This robot offers a cost-effective, modular, and efficient way to reduce foot and tire traffic on the soil and hence maintain soil health making farming more sustainable.

The integration of robotics and automation in soil health management has opened new avenues for enhancing agricultural practices. Drones and robots equipped with various sensors and imaging technology are being used to collect high-resolution data, monitoring crop health and asses soil properties.

3.9 Challenges and Opportunities for Small Land Holding Farmers

Though the adoption of A.I offers potential benefits, it comes with several disadvantages such as privacy and security concerns, high initial cost, requirement of technical expertise, small landholding patterns and complexity in integrating with traditional practices where farmers may face difficulties adapting to new A.I practices. Therefore, an alternative low-cost technology for small land-holding farmers such as easy to use and cost- efficient technology can be a reliable option. One such is the Arya Agro & Automation Pvt. Ltd, the company has developed a low-cost soil moisture sensor priced at Rs. 2,500, which enables farmers to make informed irrigation decisions and conserve water effectively (Narsi, 2024). A reliable mobile app that provides AI-based agricultural information, can tackle the challenges of adopting AI technology. Others such as disease and pest detection, crop-based weather forecasting information etc can help small farmers optimize their operations and enhance crop yields through intelligent decision-making tools. One example of affordable and easy to use invention, is Bhu Parikshak, a portable soil testing device that is compatible with smartphones (Nitnaware, 2021). Another example is NutriSens, a compact hardware device that allows for the collection and testing of multiple samples in a remarkably short amount of time (Gupta, 2023).

KrishiTantra, an agritech startup, established local soil testing centres using machine learning technology, providing farmers with quick insights into soil health with proper fertilizer recommendations (Janakiram, 2024).

As technology advances, AI's role in agriculture will grow, tackling food security and promoting sustainability. Successful implementation will require continuous collaboration among technologists, farmers, policymakers, and experts to ensure AI solutions are accessible, ethical, and beneficial for all. PM-Kisan Yojana a Government initiatives promotes the adoption of precision agriculture technology among India's farming community. Saagu Baagu is a program that introduced an array of AI-based solutions to assist farmers tackle traditional agricultural challenges. A key feature is a WhatsApp chat box created in collaboration with Digital Green and open-source developer Glific. (Janakiram, 2024). In Andhra Pradesh, India, a collaboration between ICRISAT and Microsoft provided AI-driven text messages on sowing advisories, resulting to a 30% increase in crop yields. Additionally, Microsoft's collaboration with United Phosphorous in India led to Pest Risk Prediction API, leveraging AI to predict pest attacks and minimize crop loss. In Telangana, the government is using AI for agricultural price forecasting, assisting farmers in making better crop sales decision (Janakiram, 2024).These examples illustrate the expanding impact of AI in agriculture, emphasizing its ability to tackle key challenges faced by farmers in developing nations while fostering sustainable and profitable farming practices worldwide.

4. CONCLUSION

Organic farming plays a crucial role in supporting ecosystems and creating a sustainable environment. Its benefits include reduced chemical use, improved soil health, better soil and water conservation, and climate change mitigation. However, its full potential can only be realized through innovation, supportive policies, and ongoing research. While organic farming offers significant environmental and socio-economic advantages, farmers often face higher production costs due to labor-intensive practices, and the challenges of managing sowing times, pests, diseases, and adapting to climate change. AI can offer promising solutions, but affordable, low-cost technologies and smart innovations—especially those suitable for small-scale farmers—can further ease farming practices. As the world digitalizes, AI holds the potential to revolutionize farming, offering more efficient, productive, and sustainable solutions to feed a growing population. Successful implementation will require collaboration between technologists, agriculturists, policymakers, and farmers to ensure that AI is accessible, ethical, and beneficial to all stakeholders. Focusing on affordable sensors, developing improved local innovations, and deploying existing cost-effective agricultural technologies can increase efficiency, improve crop yields, and contribute to sustainable farming by reducing resource overuse, including water, fertilizers, and pesticides. Enhancing rural internet connectivity, providing farmers with clear, accessible information, and promoting data literacy through collaboration with NGOs and farmer organizations can strengthen farmers' economic resilience and help maintain soil health by minimizing excessive chemical use and unsustainable practices.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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