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13. Sustainable Soil Management and Climate Change

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Abstract:

The integration of sustainable soil management is imperative for any initiative addressing climate change, enhancing renewable freshwater resources, restoring degraded ecosystems, and promoting food security. India's agricultural sector, vital for the sustenance of millions in rural communities, faces a significant threat to its sustainability due to the adverse impacts of climate change. Sustainable farming practices, offering substantial environmental benefits and aiding in mitigating climate change impacts compared to conventional methods, are explored in this article. The effects of various practices such as organic amendment, no-tillage, bioremediation, residue management, intercropping, chemical and organic reclamation, integrated nutrient management, and biochar on soil improvement, along with their influencing factors and associated economic benefits, are examined. Soil degradation, encompassing physical, chemical, and biological aspects, has become a serious issue affecting crop production in both rainfed and irrigated regions. Anthropogenic salt accumulation, especially secondary salinization, poses a threat to sustainable crop production and food security. The underutilization or mismanagement of waste, including agricultural residues, contributes to soil degradation and a lack of organic reserves. Utilizing the microbial potential in waste decomposition and biofertilization emerges as a crucial strategy for enhancing soil health and crop production to meet the increasing demands of the population while preserving environmental quality. The article covers management options for improving soil physical health through indigenous resources, efficient handling of saline and sodic soils, and the effective recycling of organic wastes, including crop residues and soil test-based nutrient management. Long-term experimental experiences are discussed, offering insights into efficient soil resource management for sustainable crop production. Urban agriculture and green roofs are highlighted as innovative solutions to reduce the burden on production chains in both urban and non-urban areas, promoting the recycling of by-products. Research priorities focus on sustainable soil and water management options, as well as advocating judicious soil governance to ensure essential ecosystem services.

Keywords:

soil quality; food security; greenhouse effect; conservation agriculture

13.1 Introduction:

To sustainably meet the growing demand for food in India, approximately 311 million tons of food grains will be needed by 2030 for a population of 1.43 billion, and this requirement is expected to rise to 350 million tons by 2050 when the population is projected to reach 1.8 billion. Managing soil and water resources efficiently, harmoniously, and sustainably becomes a top priority to synergize efforts for sustainable crop production.

Soil, as the ultimate source of mineral nutrients for terrestrial organisms, plays a crucial role in sustaining life. Proper soil management prevents mineral deficiencies or toxicities in plants, ensuring the entry of appropriate elements into the food chain. This directly and indirectly impacts crop productivity, environmental sustainability, and human health.

The global population of 7.2 billion and an atmospheric CO2 concentration of 400 ppmv in 2013 are increasing annually by 75 million people and 2.2 ppmv, respectively. There exists a strong correlation between human population growth and CO2 emissions, where an increase of one billion in world population leads to a 1.4 Pg increase in CO2 emissions from fossil fuel consumption. With the projected population reaching 9.6 billion by 2050 and 11 billion by 2100, CO2 emissions are expected to rise significantly. The competition for soil, water, and energy resources intensifies due to anthropogenic factors like soil degradation, climate change, water quality concerns, energy input efficiency, and global food security.

Climate change impacts on agricultural productivity and food supply are strongly influenced by soil degradation, drought, and heat stress during flowering. Seasonal heat extremes can worsen future food insecurity, making it crucial to address the impact of climate change on soil quality. The role of world soils as sources or sinks of greenhouse gases (GHGs) gains attention, especially in efforts to limit global warming. With an additional 2.4 billion people by 2050 and 3.8 billion by 2100, increased food production is essential, considering both population growth and changing dietary preferences.

Soil loss through erosion, mineral imbalance, or deforestation remains a significant threat to agricultural productivity globally. Around 38% of degraded agricultural land globally, as estimated more than two decades ago, results from anthropogenic reasons. In India, soil losses, including carbon, nitrogen, phosphorus, potassium, calcium, magnesium, manganese, and zinc, have been reported following deforestation and shifting cultivation practices. Implementing appropriate soil management systems, such as zero or minimum tillage, mulching, cover crop cultivation, and addressing acidic or salty soils, can mitigate soil losses, enhance soil organic matter, improve physical properties, and sustain water resources.

India is host of diverse soil types, grouped broadly to Alluvial, Black, Red, Laterite, Forest/Mountain, Saline and Alkaline, and Peaty/Organic, necessitate varied soil management approaches based on factors like genesis, color, composition, and location.

The article emphasizes the importance and technological options for sustainable soil management in the face of a changing and variable climate to ensure sufficient food production.

13.2 Soil Physical Quality Improvement:

The deterioration of the physical structure of soil poses a significant challenge, impacting crop production in both rainfed and irrigated regions of India. An estimate suggests that approximately 90 million hectares of land in the country are currently facing soil physical constraints (refer to Table 13.1). These constraints curtail the potential for crop production and have a severe negative impact on crop yields.

Table 13.1: Distribution of area (million ha) affected by various soil physical constraints in India (Indoria et al 2017)

Physical constraints	**Area**	**Main states affected**
Shallow depth	26.40	AP, Maharashtra, WB, Kerala and Gujarat
Soil hardening	21.57	AP, Maharashtra and Bihar
High permeability	13.75	Rajasthan, WB, Gujarat, Punjab and TN
Subsurface hard pan	11.31	Maharashtra, Punjab, Bihar, Rajasthan, WB and TN
Surface crusting	10.25	Haryana, Punjab, WB, Odisha and Gujarat
Temporary waterlogging	6.24	Madhya Pradesh, Maharashtra, Punjab, Gujarat, Kerala and Odisha

Soil physical degradation in India stems from various factors, including: (i) water erosion, which removes topsoil along with organic matter, exposing subsurface horizons; (ii) intensive deep tillage and inversion tillage using mouldboard and disc plough, leading to the disruption of stable soil aggregates; (iii) repeated cultivation; (iv) monocropping without implementing suitable rotation practices; (v) nutrient imbalance; (vi) limited use of organic manure; (vii) vegetation removal; and (viii) uncontrolled and excessive grazing.

a. Residue mulching in crust prone soils: The rapid and irreversible hardening of red chalka soils when exposed to drying poses a significant challenge for rainfed crop production. Utilizing slow-decomposing residues like paddy husk, coir pith, etc., followed by appropriate tillage has proven effective in addressing this constraint. In these soils, the addition of paddy husk at a rate of 5 t ha–1 resulted in an 18% increase in the yield of sorghum and a 23% increase in the yield of castor, as observed in the farmer's field compared to the control. Additionally, applying farmyard manure (FYM) on seed lines as mulch demonstrated notable benefits, enhancing seedling emergence three- to tenfold in pearl millet and cotton, respectively (Indoria et al., 2016). Mulching with FYM on seed lines led to improved seedling emergence, prevented crust formation, and increased crop yields, with pearlmillet increasing from 2.63 to 3.42 t ha–1 and cotton from 0.35 to 1.49 t ha–1.

b. Soil compaction technology for coarse texture soils: In soils characterized by a light texture, around 25–40% of rainfall has the ability to percolate beneath the crop root zone, enabling the conservation of a limited amount of rainfall in situ. As a consequence, rainfed crops encounter difficulties in sustaining themselves during brief dry spells exceeding 10 days. Various researchers have explored soil compaction through multiple passes of a heavy-duty roller. As reported by Indoria et al. (2016), compacted soil retained 15–33%

more moisture across different soil layers under rainfed conditions. The study also observed a reduction in saturated hydraulic conductivity by 13–25% compared to the control, possibly due to an increase in bulk density resulting from the compaction process.

c. Addition of clay and tank silt rainfed coarse soils: Conducting an array of studies in rainfed regions, particularly in Aridisols and red Alfisol soils, has shed light on the transformative effects of clay integration on the yield potential of rainfed crops. Application of tank silt at a generous rate of 60 tons per hectare, showcasing a noteworthy 2% enhancement in available water retention in red Alfisol soil in Andhra Pradesh, as elucidated by Rao et al. (2013). Osman (2008) further attested that varied rates of tank silt addition not only improved available water content but also prolonged moisture retention, supporting crops for an additional 4 to 7 days, especially crucial during prolonged dry spells and intermittent droughts.

These observed advantages are likely attributed to the formation of aggregates in light soils, facilitating increased water and nutrient retention by mitigating percolation through the addition of clay. This technology finds practical application in regions where fine-textured soil is conveniently accessible, either from ponds or nearby fields.

Tank silt emerges as a valuable resource, boasting high water retention capacity and a rich nutrient profile, serving as a sustainable alternative to traditional fertilizers and making notable contributions to climate change mitigation. Analyses conducted across various tanks in Warangal, Anantapur, and Nalgonda districts of Andhra Pradesh underscore the substantial potential of tank silt in supplying crucial organic carbon and essential nutrients. Desilting operations in Warangal revealed the presence of all essential nutrients in quantities conducive to plant growth. The recycling of tank silt effectively addresses nutrient deficiencies, particularly in zinc, boron, and sulfur, while enhancing soil organic carbon, leading to improved soil physical properties. Beyond this, tank silt proves to be a bountiful source of both organic carbon and mineral nutrients, significantly boosting moisture retention by 4 to 7 days—an invaluable advantage in the face of prolonged dry spells and intermittent droughts (Srinivasarao et al., 2013).

d. Management of subsurface mechanical impedance and compactness: The development of a compacted layer beneath the ploughing depths acts as a barrier, limiting the penetration of rainwater into the subsoil and impeding root growth. The mechanical disruption of these compacted layers, achieved through methods such as chiselling or mouldboard ploughing, proves effective in enhancing both infiltration and the water storage capacity of the soil profile. This process leads to substantial improvements in crop yields in rainfed regions. In black soils, the application of gypsum at a rate of 2-5 tons per hectare resulted in a notable increase in the infiltration rate, ranging from 4 to 7 times higher than the control rate of 0.25 cm per hour, as reported by Indiria et al. (2016).

e. Summer deep ploughing: Conducting deep ploughing during the summer season proves to be an effective measure in alleviating the adverse effects of subsurface mechanical impedance and compactness. The presence of a hard pan beneath the ploughing depths hinders rainwater infiltration into the subsoil and restricts root proliferation.

Utilizing mechanical methods like chiselling or mouldboard ploughing to break up these hard pans contributes to enhanced infiltration and increased water storage capacity in the soil profile. This, in turn, results in significant improvements in crop yields in rainfed regions.

f. Integrated nutrient management on soil physical health and crop performance: Revolutionizing nutrient supply practices, an integrated approach harmonizing organic and inorganic sources emerges as a potent strategy for elevating water use efficiency (WUE) and amplifying rainfed soybean yields in the Vertisols of central India. This holistic method not only enhances the overall soil physical conditions, fostering superior aggregation, heightened saturated hydraulic conductivity, reduced mechanical resistance and bulk density but also sparks a surge in root proliferation for rainfed soybean. Bandyopadhyay et al. (2010) conducted pioneering research, unveiling a remarkable transformation in soil properties under integrated nutrient management. They reported a significant drop in bulk density (9.3%), soil penetration resistance (42.6%), alongside an impressive surge in hydraulic conductivity (95.8%), mean weight diameter of water-stable aggregates (13.8%), and soil organic carbon content (45.2%) compared to the control group. The annual ritual of applying 4 tons per hectare of farmyard manure (FYM) alongside the recommended fertilizer dose (NPK) demonstrated a substantial upliftment, propelling rainfed soybean grain yields by 14.2% beyond the NPK treatment and a staggering 50.3% over the control group. The amalgamation of NPK + FYM not only showcased enhanced WUE but also outperformed NPK and the control.

Other studies also reveal a consistent trend of heightened WUE in rainfed soybean under the umbrella of integrated fertilizer and FYM practices in Vertisols. Transitioning to moisture content improvements, the application of tank silt, especially in synergy with FYM at diverse Okra growth stages, induced a significant boost. Treatment T3, featuring tank silt at 10 tons per hectare + recommended fertilizers, emerged as the frontrunner in soil moisture content at depths of 0-15cm and 15-30cm. Following closely was T7, showcasing tank silt at 5 tons per hectare + FYM at 2.5 tons per hectare + recommended fertilizers. This leap in performance significantly overshadowed other treatments (Kadam et al., 2017). Notably, the treatment with tank silt applied at 5 tons per hectare + FYM at 2.5 tons per hectare + recommended fertilizers exhibited the pinnacle of nutrient availability per hectare. The study thus underscores the transformative potential of integrated nutrient management practices in elevating both soil health and crop productivity.

g. Management of Black clay soils: In India black clay soils constitute about 54 M ha distributing mostly in and around Maharashtra. The main constraint of crop production in black soils (Vertisols) are due to their narrow workable moisture, low infiltration rate, poor drainage and moisture stress. They are generally rich in calcium but are deficient in nitrogen, phosphorus, sulpher, zinc and boron. The calcareous nature of these soils affects the availability of many micronutrients. Because of high water holding capacity, these soils can be utilized for rainfed agriculture particularly for growing minor millets and pulses like horsegram. Upland rice suffers from iron deficiency. Groundnut, mustard are found to respond to application of sulphur. Ammonia volatization is high in paddy fields. Soil moisture stress conditions set early under drought. Either at low or high moisture conditions the soils cannot be ploughed. Tillage operations should be completed at right moisture consistency.

Application of farmyard manure (FYM), compost and green manuring help in increasing water infiltration rates (Antaryayami Mishra et al, 2011). Recycling of rice straw improves the physical conditions of these soils. The construction of 15cm high ridge on black clay soils reduces the bulk density and increases non-capillary pores indicating a better aeration and drainage capacity of soil (Jena, 2010). Grain yield of soyabean, maize and sorghum increase significantly by planting on 15 cm high ridges. The soils are suitable for growing rice, jowar, bajra, maize, bengal gram, safflower, mustard and cotton.

13.3 Soil Chemical Quality Improvement:

Chemical degradation of soils occurs by excessive use of fertilizers, faulty use of irrigation water, excessive tillage and soil erosion causing serious threat to sustainable crop production.

A. Salty Soils and Their Sustainable Management:

Navigating the realm of soil degradation induced by salinization unfolds as a formidable obstacle to agricultural prowess. Presently, an expansive 1,125 million hectares of land grapple with the repercussions of salinity, with 76 million hectares bearing the imprint of human-induced salinization and sodification. Within India's borders, the affliction touches 6.74 million hectares, with the states of Gujarat, Uttar Pradesh, and Maharashtra bearing the brunt (CSSRI, 2015).

Saline-sodic soils in the Indo-Gangetic plains: Delving into the intricate landscape of saline-sodic soils in the Indo-Gangetic plains reveals a pronounced impediment to the rice-wheat cropping system. In this backdrop, the wheat and rice yields experience staggering losses, soaring up to 40% and 45%, respectively, particularly in the North Indian River Plain (Tripathi, 2009). Projections cast a looming shadow, foretelling that by 2050, half of the world's agricultural expanse will succumb to the clutches of salinity (Bartels and Sunkar, 2005).

To counteract this, a multifaceted strategy for the reclamation of salt-affected soils is needed. The strategies include physical amelioration techniques like subsoiling, deep ploughing, and sanding, along with chemical interventions involving gypsum, calcium chloride, limestone, sulfuric acid, sulfur, and iron sulfate.

The repertoire also encompasses electro-reclamation and biological amelioration methods, capitalizing on crops, stems, straw, green manure, farmyard manure, and sewage sludge. Noteworthy among these, compost amendment stands out as a beacon of efficacy for saline-sodic soils. Its transformative impact extends to enhancing soil structure and permeability, facilitating salt leaching, and catalyzing the release of carbon dioxide during respiration and decomposition (Sreenivasan et al., 2015). Furthermore, the application of compost to plants becomes a bestower of essential macro-nutrients like nitrogen (N), potassium (K), and phosphorus (P), alongside an array of micro-nutrients including iron (Fe), magnesium (Mg), copper (Cu), zinc (Zn), and boron (B). This orchestrated nutrient symphony not only fortifies the soil but also orchestrates a harmonious enhancement of microbial activity (Barman et al., 2014).

I. Gypsum and Muncipal Solid Waste Compost for Amelioration of Saline Sodic Soils: Behzad Murtaza et al (2019) reported aerobically decomposed MSW as an effective solution for MSW disposal, thereby improving soil chemical properties and crop productivity in saline- sodic soil. Results revealed a decrease in soil pH, electrical conductivity (EC), calcium carbonate (CaCO3), and sodium adsorption ratio (SAR) with anaerobically decomposed MSW compost during rice and wheat, respectively. In this treatment, organic matter (OM) and cation exchange capacity (CEC) were increased as compared with control treatment during rice and wheat, respectively. Rice and wheat growth were significantly increased by anaerobically decomposed MSW.

II. Use of Organic Matter for Reclamation of Sodic Soils: Compost, and plant roots helps to dissolve insoluble calcium compounds. Plant roots can stimulate changes in physical characteristics of the root zone in several different ways, such as removal of air entrapped in larger conducting pores, generation of alternate wetting and drying cycles, and creation of macropores. Organic matter addition also enhances the stability of the aggregates due to the in-situ production of polysaccharides and fungal hyphae at the root-soil interface process. (Singh 1996).

III. Humic Substances (HS) And Their Impact on Soil Sodicity/Salinity and Nutrient Availability: Owing to their distinctive structural attributes, humic substances (HS) play a pivotal role in enhancing various physical and chemical aspects of soil. Notably, they exert a profound influence on aggregate stability, buffering capacity, the sorption of hydrophobic organic compounds, and the intricate dynamics of transport, bioavailability, and metal complexation within the soil environment, as outlined by Rosa et al. (2005).

The provision of HS serves as a wellspring of energy for the symbiotic organisms dwelling in the soil, thereby impacting essential facets such as soil water holding capacity, structural integrity, the gradual release of plant nutrients from soil minerals, and an augmented availability of trace minerals. These transformative effects bear paramount significance in fortifying the fertility of salt-affected soils, especially in arid regions, and are instrumental in sustaining agricultural productivity in challenging environments.

IV. Sub-Surface Drainage of Saline & Waterlogged Soils: In Andhra Pradesh, a significant portion of agricultural land, approximately 11.55 lakh ha, grapples with waterlogging issues. Innovative solutions such as perforated burnt clay tiles or corrugated PVC pipes are employed as laterals, while envelope materials like sand, coconut coir, geo-textile, and nylon mesh are strategically utilized to prevent the sedimentation of soil particles within the system. The effective leaching of soluble salts through the Sub-Surface Drainage (SSD) system amounts to 3.53 t/ha/annum.

The implementation cost of the SSD system ranges from Rs.24,000 to Rs.29,000 per hectare for a 30 m spacing, with a subsequent reduction in cost as the spacing increases. An economic evaluation of the SSD system reveals a commendable Benefit-Cost (B-C) ratio of 1.24 and an internal rate of return of 39.07% under mono-cropping conditions (Lakshmi et al., 2015). The adoption of sub-surface drainage technology in saline soils has translated into a remarkable threefold increase in farmers' income. Paddy, wheat, and cotton yields witnessed substantial increments of approximately 45%, 111%, and 215%, respectively, showcasing the transformative impact of this drainage approach (Sharma et al., 2014).

V. Phytoremediation of Salt-Affected Soils: Phytoremediation of salt-affected soils refers to the processes of removing excess salts from soil by growing different type of plants. Growing of salt tolerant trees, shrubs, and grasses is a cost-effective and environmental-friendly way of restoring salt- affected soils (Qadir et al., 2007).

VI. Salt tolerant crops: Cultivation of salt tolerant crops and crop varieties is another way to address the problem of soil salinization. This technique is viable and cost effective and suits well to the small and marginal farmers who without financial support are unable to bear the high costs of chemical amendment-based reclamation technologies. Salt tolerant varieties of rice, wheat, mustard, and other crops, grasses, shrubs, fruit trees, and medicinal and aromatic plants have been developed/identified for commercial cultivation in salt-affected soils.

VII. Bioremediation of Salty Soils: A low-cost microbial bio-formulation “CSR-BIO,” a consortium of *Bacillus pumilus*, *Bacillus thuringenesis,* and *Trichoderma harzianum,* is rapidly becoming popular with the farmers in many states (Damodaran et al., 2013). This bio-formulation acts as a soil conditioner and nutrient mobilizer and has been found to increase the productivity of the high value crops such as banana, vegetables, and gladiolus in sodic and normal soils by 22–43%.

B. Acid Soils and Their Sustainable Management:

Soil acidity is a serious constraint to crop production in many regions of the world including India. Acidic soils in India are mainly prevalent in the humid Southwestern, Northeastern and Himalayan regions. They are particularly acute in the humid tropical regions that have been subjected to severe weathering. In India, about 48 m ha out of 142 m ha of arable land are affected by acidity, of which 25 m ha have pH below 5.5 and 23 m ha have pH between 5.6 and 6.5 (Gurumurthy, 2021). Strongly acidic and moderately acidic soils cover 6.24 m ha (1.9%) and 24.41 m ha (7.4%), respectively of the country’s total geographic area (Maji et al. 2012). In the Northeastern region, approximately 95% of the soils are acidic and nearly 65% have strong acidity with pH below 5.5 (Sharma and Singh 2002). Maximum area under Arunachal Pradesh (6.8 Mha) followed by Assam (4.7 Mha), Meghalaya, (2.24 Mha), Manipur (2.19 Mha) and Mizoram (2.0 Mha). Soils of Odisha account for 70% of its total geographical area as acidic (Jena 2010).

i. Liming Technology:

Liming serves as a valuable practice in soil management, addressing issues of soil acidity and enhancing various soil properties. It effectively raises soil pH, improves base saturation, and increases cation exchange capacity (CEC). Additionally, liming enhances nutrient availability, transforms insoluble soil complexes of phosphorus (P) and sulfur (S) into more accessible forms for plants, fosters biological activity, and promotes nitrogen fixation by legumes. The application of liming also contributes to the improvement of soil physical structure, reduces toxicities of iron (Fe), aluminum (Al), and manganese (Mn), optimizes the effectiveness of certain herbicides, and ultimately leads to increased crop yields. Various liming materials, including burned lime (CaO), hydrated lime (Ca (OH)2), and wood ashes, are also considered.

The primary outcomes of liming include the increase in available phosphorus by addressing exchangeable and soluble aluminum and iron hydroxides, elevation of pH, available phosphorus, exchangeable cations, and percentage base saturation. Liming further enhances root hair density and length, facilitating improved phosphorus uptake. Consequently, liming corrects toxicity concerns related to excess soluble aluminum, iron, and manganese, promoting root growth and enhancing nutrient uptake. It also stimulates microbial activities, contributing to nitrogen fixation and mineralization, particularly benefiting legumes.

The residual effects of liming are anticipated to last for five to seven years. Research indicates that the efficiency of lime becomes more pronounced in subsequent years, with the highest barley yield observed in the third year after lime application in Ethiopia. Adequate lime application, typically in the range of 200–400 kg per hectare per year, is reported to maintain calcium and magnesium levels in the soil while mitigating the release of exchangeable aluminum.

ii. Biochar as Amendment to Acid Soils:

Combining moderate biochar application rates (e.g., 2 to 4%) with lime, equivalent to exchangeable acidity or around 2 tons/ha for most acidic soils in Hawaii, has been demonstrated to substantially enhance soil quality and promote crop growth (Berek et al., 2011). The introduction of lime predictably heightened plant growth by elevating soil pH and reducing aluminum toxicity, as aluminum precipitated out of solution, rendering it non-toxic to crops.

Likewise, the utilization of biogas slurry, crop residues, and organic materials such as biochar presents effective options for managing acidic soils. Pyrolytic biochar, serving as a soil amendment, proves beneficial in improving soil fertility and mitigating soil acidity. Unlike direct incorporation of plant materials into soils, which has short-lived effects due to rapid decomposition by microorganisms, biochar is recalcitrant and may persist in soils for hundreds of years. Natural coal and coal extracts have also demonstrated their ability to ameliorate acidic soils and enhance root growth.

Biochar application induces a significant increase in pH and phosphorus retention in slightly acidic soils. Additionally, it results in reduced bulk density, increased porosity, cation exchange capacity (CEC), organic carbon content, moisture holding capacity (MWHC), infiltration rate (IR), and saturated hydraulic conductivity (SHC) (Gowthami and Gurumurthy, 2019).

Notably, the rhizosphere microbiome, including microbial population and soil enzymes like urease, dehydrogenase, acid and alkaline phosphatase, exhibits a substantial increase with biochar addition to sandy loam soils compared to treatments without biochar. At an application rate of 6 t ha-1, biochar significantly enhances microbial population and enzyme activities, surpassing the effects observed at 2 t ha-1 and control treatments. The growth, biomass production, and pod yield of groundnut also experienced a marked increase with biochar application. Higher pod yields were recorded with biochar applied at rates of 6 t ha-1 + 100% RDF, 4 t ha-1 + 100% RDF, and 6 t ha-1 + 75% RDF, demonstrating a significant improvement compared to control and RDF-alone treatments.

Growing acid tolerant crops: Aluminium toxicity limits crop production in acidic soils, to which soil liming is the answer. However, considering the huge quantities of lime and associated costs involved in amelioration of these soils, growing acid-tolerant crops and cultivars might be a viable alternative. Blueberries, potatoes and watermelons tend to be more acid tolerant than crops like corn, soybean, wheat, alfalfa and clover. Wheat has proven to be a useful crop in this respect, with up to 10-fold difference in Al tolerance amongits genotypes compared to other cereals. Paddy is a good choice because flooding neutralizes the acidity and associated negative effects where water is abundantly available.

iii. Rhizosphere Management in Acid Soils:

Depending on the pH, clay, organic matter, sesquioxides and phosphorous fixing ability of acidic soils, P applied as water soluble Single Super Phosphate (SSP) is often transformed into aluminium and iron-bound complexes within 24 hours of application and may become unavailable for uptake by plants. Such fixation has been observed to be less in the case of Rock Phosphate (RP). Under such circumstances, rhizosphere-based P management might be useful in enhancing phosphoroususe efficiency in acidic soils (Kalidas-Singh et al. 2013). This involves synchronization of P mineralization rate in the rhizosphere with P uptake by the plant during various growth phases, minimizing phosphorousfixation in the rhizosphere and increasing tissue phosphorous concentration for better root development during the initial stages of crop growth.

These may be achieved by building up the population of Phosphate Solubilizing Microorganisms (PSM) in the rhizosphere, slow release of P over a long duration through combined application of PSM and RP and root dipping of seedlings in a orthophosphate solution. Phosphate Solubilizing Bacteria (PSB) can dissolve the bound forms of phosphates into available monocalcium phosphate in the soils. This occursdue to exudation of organic acids (e.g., gluconic acid), release of pathogen-suppressing metabolites likesiderophores, phytohormones and lytic enzymes, and increase in phosphatases activity in the roots to hydrolyse organic P compounds to improve P acquisition by the plant.

13.4 Organic Amendments for Sustainable Soil Management:

A. Green leaf manures: *Gliricidia* addition improves mobilization of native soil nutrients in the soil due to production of carbon dioxide and organic acids during decomposition of the plant material, adds valuable nutrients such as N, P, K, Ca, and Mg to the soil. Application of 1 t ha^{-1} *gliricidia* leaf manure provides 21 kg N, 2.5 kg P, 18 kg K, 85 g Zn, 164 g Mn, 365 g Cu, 728 g Fe besides considerable quantities of S, Ca, Mg, B, Mo etc. (Fig. 1). Legume crops like chickpea, soybean, groundnut, blackgram, greengram, pigeonpea do not need any additional N application, if 2 t *gliricidia* leaf manure per ha is applied. Micronutrient requirement is also mostly met through addition of 2 t *gliricidia* ha^{-1} for major rainfed crops (Srinivasarao *et al.,* 2011)

B. Green manures (GM): Besides Sunhemp, Dhainha, Horsegram (*Macrotyloma uniflorum*) is sown late in the rainy season by resource-poor farmers in marginal, drought-prone areas of India. Horsegram is a legume crop with a low requirement for water that quickly produces N rich foliage. Horsegram as a cover crop was introduced in the rainfed dryland districts of Ananthapur and Rangareddy to improve soil health and water retention. After harvest, *kharif* crop horsegram was grown by utilizing off-season rainfall received to the extent of 20% and incorporated into soil at the flowering stage and reported production of 3.03- 4.28 t ha-1 year-1 (fresh weight) biomass (Srinivasa rao et al.,2013). Due to improved organic matter and nutrient supplementation the succeeding crops in the system were benefited.

C. Vermicompost: Vermicompost preparation is practiced in the rainfed tribal districts of Telangana and Andhra Pradesh particularly in Nalgonda, Rangareddy, Mahboobnagar, Warangal, Khammam and Kadapa. In the studied districts, vermicomposting played a critical role as drought proofing in the years 2009-2012. In these districts, the water holding capacity (WHC) of the soil. increased with increased application rates of vermicompost and was significantly greater in the vermicompost–soil mixture than the control treatment. Studies by Fauziah and Agamuthu, (2009) have shown that the average water holding capacity of vermicompost was 25% while its total organic carbon content was 12%.

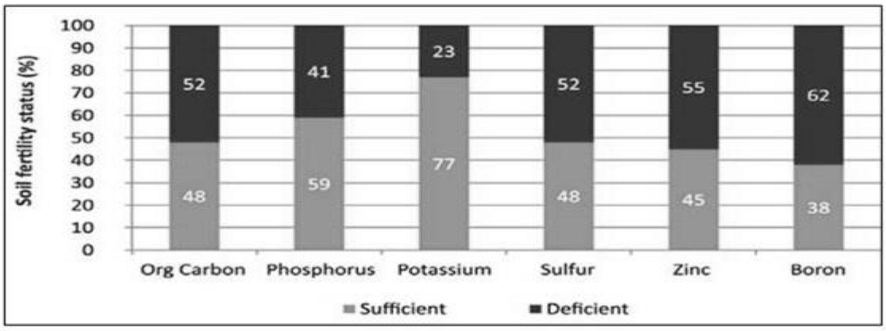
D. Crop residue recycling: Organic matter plays a crucial role as a soil component, influencing various factors associated with crop productivity. The decline in soil fertility and crop production is often linked to the reduction in soil organic matter levels. Maintaining soil organic matter can be achieved through the addition of crop residues, making Crop Residue Management (CRM) vital for both soil health and crop production. In India, the availability of crop residue is estimated to be 300, 343, and 496 million tonnes in 2000, 2010, and 2025, respectively. Crop residues, essential for sustainable agriculture with minimal external inputs, enhance the physical, chemical, and biological properties of the soil, consequently improving crop productivity.

While crop residue can partially substitute fertilizer nutrients, it cannot entirely replace them. However, it has the potential to elevate the fertility status of the soil. Rice, wheat, and oilseed crops contribute three-fourths of the total residue, with the remaining one-fourth originating from sugarcane and sorghum. The distribution of available residue for incorporation is 53% in Kharif and 47% in the Rabi season (Indra Bahadur et al., 2015).

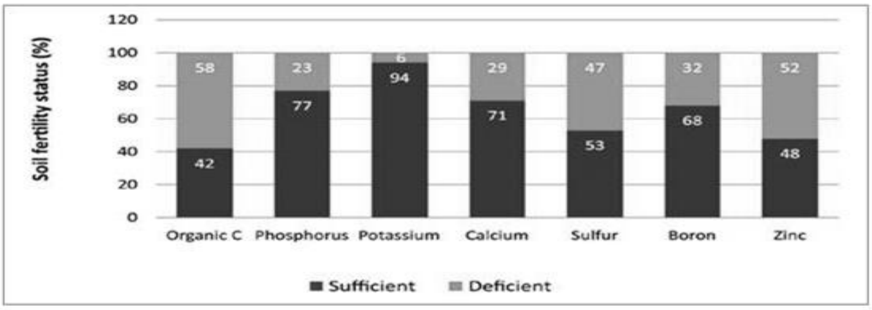
Crop residue significantly contributes to soil organic matter, promoting nutrient availability, water retention, and microbial and macro-invertebrate activity. In a study, an increase in ground cover by maize residues was associated with a consistent 2% rise in water storage following the onset of spring rains. The mulching effect of stubble and crop residue on the soil surface was attributed to reducing water loss through evaporation and enhancing water infiltration by minimizing runoff. Furthermore, increased nutrient supply and notable improvements in soil health were observed with the augmentation of carbon accumulation (sequestration) through the recycling of organic residues, such as crop residues.

13.5 Soil Test-Based Fertility Management:

Deterioration in soil fertility and the widespread prevalence of nutrient deficiencies, especially of micronutrients, posed a threat to soil health, the productive performance of crops, incomes of millions ofsmallholder farmers. A detailed survey of soil fertility was takenup by ICRISAT between 2014-2016 in AP, Karnataka, Odisha (Fig.1) by analyzing about one lakh soil samples from farmers' fields of each state. The consultations with respective SAUs and state department of agriculture outshaped with the following recommendation: Application of 25% more NPK in case of low nutrient status and 25% less NPK when nutrient status is high. Critical levels of deficiency for S, Zn, B, Cu, Fe and Mn are 10 mg/kg, 0.6 mg/kg, 0.5 mg/kg, 0.2 mg/kg, 4.5 mg/kg and 2 mg/kg, respectively; Yearly recommended dosage of boron is 1 kg/ha; The recommended dosage of sulfur is 30 kg/ha in cereals (i.e., 200 kg/ha through gypsum), 40 kg/ha in pulses and 45 kg/ha in oilseed crops; In the case of zinc, the recommended dosage is 5 kg/ha in paddy, 2.5 kg/ha in pulses and 2.0 kg/ha in oilseeds; Large-scale promotion of aerobic composting both at individual and community levels; Promote the application of well decomposed poultry manure @ 2.5 t/ha in furrows as a substitute for lime in acid soil management.



Soil fertility status of farmers' fields in Karnataka, India (Chander et al. 2016).



Soil fertility status of farmers' fields in Andhra Pradesh, India (Wani et al. 2018).

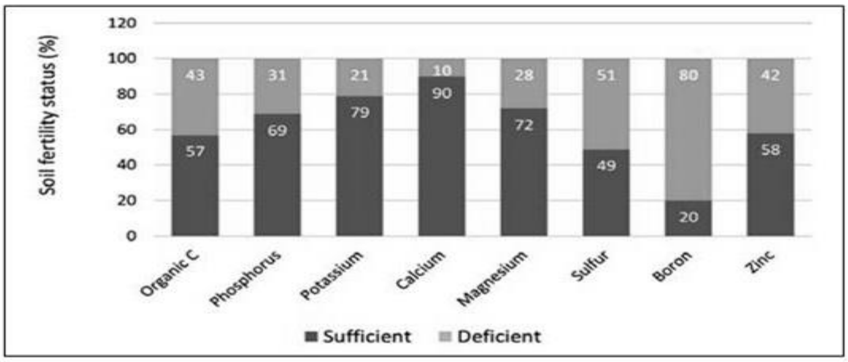


Figure. 13.1: Soil fertility status of Karnataka, AP and Odisha states.

13.6 Climate smart agricultural practices:

Good management practices to increase soil organic matter include, direct seeding (no-tillage) in combination with protective soil cover, crop diversification and crop rotation;the elimination of the burning of crop residues; integrated soil fertility management to increase the soil's nutrient retention capacity and the availability onnutrients to plants;

The precise management of nitrogen; integrated pest management, which includes the sustainable use of herbicides.

The construction of soil conservation structures, such as stone and earth terraces and bunds, and check dams;irrigation or partial irrigation where needed or possible; the harvesting and proper use of rainwater; the development of reliable sources of information and extension services that are tailored to localconditions; and appropriate soil erosion control practices.

Table: 13.1 Conventional soil management practices versus climate-smart practices

Conventional soil fertility management practices	Climate-smart practices for climate change adaptation	Climate-smart practices for climate change mitigation
Soil fertility management through syntheticfertilizers	**Integrated soil fertility management**	
- The manufacturing, processing and applying synthetic nitrogen fertilizers emit considerable greenhouse gases. Mechanical incorporation of fertilizers through ploughing, or minimum tillage, forexample, disrupts the soil and the formation of new aggregates. It also encourages microbial activity, which contributes to the rapid mineralization of soil organic matter. - Fertilizers may contain hazardous by-products thatcan accumulate in the soil and may pollute the soil and groundwater. - Soil micro-organisms mineralize organically boundnitrogen and release ammonia, which in turn is transformed into ammonium ions, and	- Maximizing the use of organic matter sources (e.g. compost, animal manure and green manure) is a cost-efficient means to replenish soil organic matter content. Enhancing nutrient efficiency through crop rotations or intercropping with nitrogen-fixing crops, and the judicious and precise use of soil amendments and nutrients reduces nutrient inputs and losses.	- Reducing the input of synthetic nitrogen fertilizers reduces carbon dioxide emissions that result from their production, and nitrous oxide emissions that result from their application of these inputs and consequent ammonia volatilization. - Using enhanced efficiency fertilizers (e.g.,slow-release fertilizers or fertilizers with urease or nitrification inhibitors) reduces ammonia volatilization and nitrous oxide emissions. - Using appropriate placement of nitrogen fertilizer near the zone of active root uptake and synchronizing the timing

Conventional soil fertility management practices	Climate-smart practices for climate change adaptation	Climate-smart practices for climate change mitigation
further nitrified into nitrates. - Nitrate ions can be leached from the soil through drainage. In oxygen-limited soils, denitrifying organisms will reduce nitrates to nitrous oxide, a greenhouse gas with about 300 times more warming effect than that of carbon dioxide.		of nitrogen fertilizer application with plant nitrogen demand reduces inputs, decreases nutrient losses and lowers greenhouse gas emissions.
Soil tillage for annual crops	**Conservation agriculture**	
Tillage is done to control weeds and loosen the soil. However, when loose soil is left under the impact of rain, wind and heat, the topsoil gets eroded. This lowers the natural content of soil organic matter, reducing soil fertility and releasing carbon dioxide. It also reduces the presence of soil organisms (e.g. earthworms, fungi), which limits the soil's capacity to regain its fertility. Tillage also typically develops a compacted layer (hardpan), which impedes plant root growth and rainwater infiltration.	Conservation agriculture increases the resilience of the farming systems in a number of ways. - Soil is kept fertile and protected from erosion and evaporation. - Water and nutrients are used efficiently. The elimination of pre-seeding operations allows maximum timeliness and flexibility in planting to accommodate weather conditions. Pre-seeding operations can be avoided by sowing seeds directly into the standing stubble of the previously harvested crop.	Conservation agriculture reduces: - carbon dioxide emissions from tractor use, as the farm power requirements are lower and fewer passes across the field are needed. - carbon dioxide emission from the production of farm machinery, as the required equipment is smaller and has a longer life; - carbon dioxide emissions from the soil relative to those released by tillage. These 'carbon savings' exceed the carbon costs related to the use of chemical herbicides for weed control. Conservation agriculture also has the potential to sequester soil organic carbon.

13.7 Experiences from Long Term Fertility Experiments:

In a comprehensive study at CRIDA, Sharma et al. (2005) underscored the necessity of primary tillage, organic residue incorporation, and nitrogen application for sustaining both yield and soil quality in rainfed Alfisols. The most effective treatment was identified as conventional tillage combined with gliricidia leaves at 2 t/ha and 90 kg N/ha, resulting in the highest Soil Quality Index (SQI). This approach proved promising for maintaining elevated average yield levels and enhanced soil quality in dryland Alfisols under sorghum–castor rotation.

The study emphasized specific indicators, such as available nitrogen (N), DTPA-Zn and Cu, microbial biomass carbon (MBC), mean weight diameter (MWD), and hydraulic conductivity (HC), as crucial factors influencing soil quality in semi-arid tropical rainfed Alfisols. These indicators played a pivotal role in determining soil functions, overall soil quality, and subsequent achievements in mean yields, Soil Yield Index (SYI) for sorghum and mung bean, and Soil Organic Carbon (SOC).

In a long-term study of rainfed rice-lentil cropping systems in Inceptisol at Varanasi, continuous application of organic manure alongside inorganic fertilizer led to a substantial 54.1% increase in soil organic carbon compared to the control treatment (Biswas et al., 2023). Principal component analysis (PCA) identified key indicators, including mean weight diameter (MWD), available iron (Fe), available nitrogen (N), mineralizable nitrogen, available zinc (Zn), FDA hydrolase activity, and clay content. The treatment with 50% NPK + FYM demonstrated the highest Soil Quality Index (SQI) of 0.95.

Gurumurthy and Srinivas (2022) conducted a study revealing varying Relative Soil Quality Index (RSQI) values across different cropping systems. The mesta-fallow cropping system in rain uplands exhibited the lowest RSQI value of 67.5, corresponding to soil quality class IV (severe limitations). In contrast, the cashew and guava systems in rainfed uplands showed the highest RSQI value of 81.75, qualifying for soil quality class II (slight limitations). Other systems, such as redgram-fallow (81.25), sapota (81.0), mango (80.75), rice-sunhemp (80.75), and rice-pulse (80.00), also fell into class II soils. Notably, rice-fallow in lowlands, rice-rice, and rice-maize cropping systems in irrigated uplands, and coconut plantation in rainfed uplands recorded a soil quality class of III with corresponding RSQI values of 76.00, 73.75, 70.05, and 72.75, respectively.

13.8 Conclusion:

Significantly increasing food production in the coming decades is imperative to meet the demands of a growing population and changing dietary preferences. However, soil and water resources, susceptible to misuse and mismanagement, are intertwined with processes influencing climate change. Sustainable intensification of agriculture, relying on proven technologies, offers a pathway to enhance food production on existing land, counteract soil and environmental degradation, and prevent the conversion of natural ecosystems into agroecosystems. Established technologies such as conservation agriculture, precision agriculture, water harvesting, micro-irrigation, agroforestry, urban agriculture, carbon sequestration, perennial cultivation, and integrated nutrient management, including biological nitrogen fixation, contribute to sustainable intensification. Priority issues include residue management, appropriate tillage systems, and subsurface tile drainage for saline clay soils, aiming to enhance soil physical health. Reclamation of acid and salt-affected soils utilizing gypsum, decomposed municipal solid waste, humic substances, and phytoremediation with salt-tolerant tree species like Sesbania aculeate proves to be cost-effective and eco-friendly.

Cultivating salt-tolerant crops and employing microbial bioformulations like CSR-BIO, a microbial consortium, are emerging practices for improving crop production in sodic soils. Effective rhizosphere management of acid soils is crucial for enhancing phosphorous and micronutrient availability. Organic amendments, including FYM, green manures, green leaf manures, vermicompost, municipal waste compost, and crop residue, play a pivotal role in soil resource management. Implementing soil test-based fertilizer management, integrated nutrient management, site-specific nutrient management, and precision farming are successful technologies contributing to sustainable crop production. Insights from long-term fertility experiments further underscore the importance of efficient organic residue management in maintaining soil physical, chemical, and biological health, ensuring sustainable crop production.

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