



REVIEW ARTICLE

Sustainable soil health management: Novel agronomic approaches and technological interventions

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Abstract

Soil is an essential natural resource that sustains plant growth by providing nutrients, water and structural support. Yet non-stop human interventions-including fertiliser use, nutrient removal, altered water balance and microbial shifts-disrupt soils' bodily, chemical and biological properties. Even small adjustments in soil pH and buffering capacity can lessen resilience. Globally, an anticipated 1036–1470 m ha of land are degraded, underscoring the pressing need to repair soil health. Traditional inputs like chemical fertilisers and manures are now not sufficient for long-term soil quality, as they regularly fail to enhance soil structure, enhance microbial range, or sustain nutrient cycling beneath intensive agriculture. This evaluation addresses this gap by using synthesising proof on holistic agronomic strategies for soil recovery. It evaluates the function of organic amendments, different nutrient sources, conservation agriculture, microbial inoculation, incorporated farming systems and soil pH-correcting amendments in enhancing soil health. Additionally, it highlights the ability of crop residues, agro-commercial via-merchandise and untreated mineral wastes (e.g., gypsum, phosphorus slag and basic slag) as sustainable amendments that help each soil achieve high-quality and crop vitamins. Overall, the assessment contributes a complete evaluation of emerging agro-techniques and their potential to improve soil fitness throughout various agro-climatic areas.

Keywords: conservation tillage; integrated farming; soil degradation; soil health

Introduction

Soil, an unconsolidated and dynamic 4-D machine, supplies vegetation with water, nutrients and mechanical help. It accommodates minerals, natural deposits and pores filled with air and water. Ideally, soil carries 45 % minerals, 5 % natural depend and 50 % pore area, maintaining plant growth by means of supplying both mineral nutrients and non-mineral elements like oxygen, carbon and hydrogen. Significant deviations in these proportions or in soil are biological, chemical and organic homes past crop tolerance motive degradation (1). Globally, soil degradation is extreme: the United Nations Convention to Combat Desertification (UNCCD) estimates 1.9 billion ha are degraded, threatening food production, ecosystems and livelihoods. Soil fitness is vital not only for productivity but also for ecosystem services, which include carbon storage, water regulation, biodiversity and weather mitigation. Healthy soils are marked by resilience, chemical balance and organic diversity, which are vital for sustaining these capabilities. Although little research checks character practices (fertilisers, natural amendments, microbial inoculation), few combine them into a holistic framework. This evaluation evaluates natural amendments, diverse nutrient assets, conservation agriculture, microbial inoculation, integrated farming systems (IFS) and pH correcting measures, highlighting their position in sustainable soil control throughout agro-climatic regions (2).

Soil health issues

Soil degradation critically influences agro ecosystems international. Healthy soils preserve crop productivity and buffer against droughts and floods, risks intensified through weather alternation. They offer key atmospheric services, nutrient biking, microbial variety and carbon sequestration, helping sustainable development goals on food protection, poverty reduction and weather resilience (3). Yet soil fitness is an increasing number of compromised. The UNCCD reviews 1.9 billion ha degraded, pushed through erosion, salinisation, nutrient loss and pollutants, with severity differing throughout regions.

Erosion: The maximum severe form of deterioration, internationally, affecting rainfed systems in Africa, South Asia and Latin America. Water erosion on my own bills for the shortage of 24 billion lots of fertile soil annually, lowering productivity and growing vulnerability to weather shocks.

Salinity: Particularly acute in irrigated command regions of South and Central Asia, the Middle East and parts of Australia. Secondary salinisation impacts an predicted 20 % of irrigated land globally, undermining food safety in areas depending on irrigation.

Nutrient depletion: A vital trouble in Sub-Saharan Africa, where continuous cultivation without replenishment has caused sizable declines in soil fertility, immediately impacting smallholder productivity (4).

Soil pollution: A growing global issue, especially in industrial and peri-urban East Asia and Europe, where heavy metals, agrochemicals and persistent pollutants accumulate.

Desertification: Concentrated in drylands of Africa and Asia, pushed by human activity and climate change, with degradation varying in scale.

Socio-economic effect: Erosion in rainfed systems hits smallholders the hardest, salinity in irrigated zones undermines large-scale meals production, even as localised pollution poses long-term dangers to food protection and ecosystem integrity. To improve resource comprehension, erosion rates, salinity-affected hectares and economic impacts are summarised in a comparative table (Fig. 1). This enables a quick assessment of their relative importance and geographic distribution, highlighting priority areas for intervention (5).

Types of soil degradation and their causes

Physical degradation of the soil

Physical soil degradation arises from tactics like crusting, compaction, hardening, wind, waves and coastal erosion. Agricultural drivers include excessive tillage, terrible timing, fluctuating moisture cycles in in-depth cereal structures, decreased

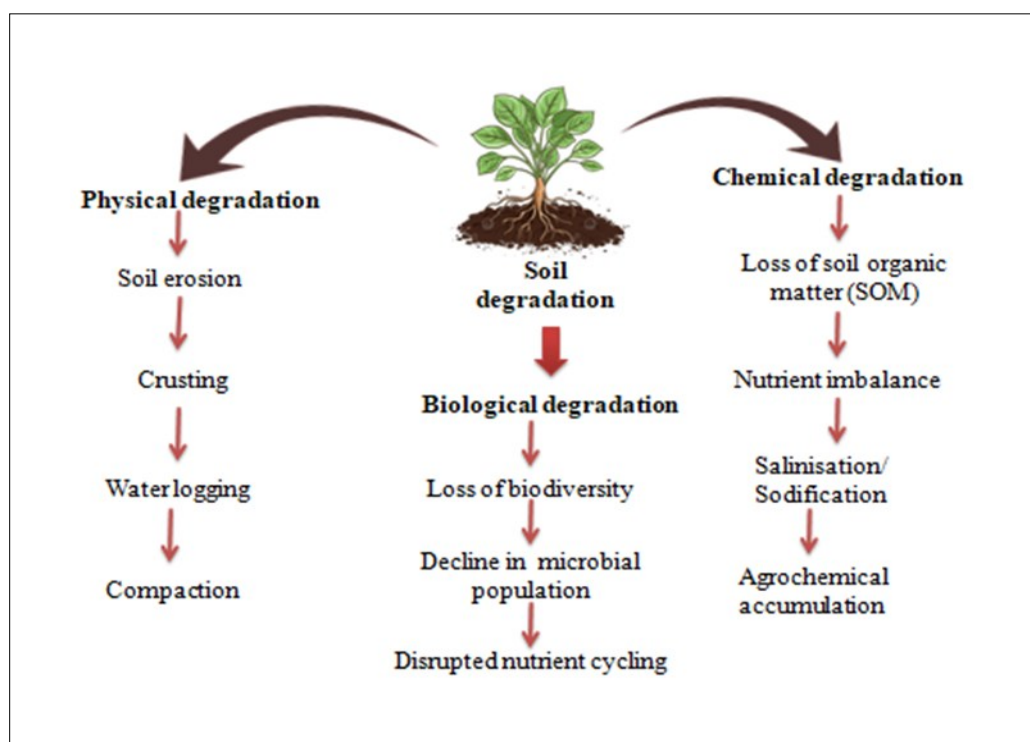


Fig. 1. Types of soil degradation and their causes.

natural manure use and complete biomass elimination, leaving soil bare. The essential causes are altered soil houses or displacement of soil fabric without replenishment (6).

Loss of soil in the area

Soil erosion is the most common form of soil degradation. Annually, 5 m lots of soil are misplaced (16.35 t/ha/yr), affecting 19.65 m km². In India, erosion influences 31.5–166.1 m ha: 94 m ha by way of water and 9 m ha by way of wind; precise estimates show 32.8 m ha affected by wind and 10.8 m ha through water (6). During erosion, soil particles detach and migrate, with 29 % permanently misplaced to the ocean (7). Soil erosion arises from more than one reasons that change with environmental and management situations. Water erosion is driven by using crop practices, soil erodibility, slope, rainfall depth and distribution and the erosive strength of sellers (8). Wind erosion depends on soil texture, floor cover, roughness and wind characteristics, along with path, breadth and the presence or absence of limitations. Wave erosion normally takes place alongside riverbanks and canal edges, in which flowing water destabilises soil. To quantify soil loss, the universal soil loss equation (USLE) is typically applied to annual erosion costs ranging from 5–80 Mg/ha (9).

Changes to the physical properties of the soil: Compaction and crusting

Soil compaction and crusting are the most important physical constraints, restricting water infiltration, root growth and crop establishment. Crusting paperwork is a thin, dense, low porosity floor layer that hastens erosion, reduces seedling emergence and disrupts hydrological stability. Globally, crusting is extreme in semi-arid and tropical zones because of excessive rainfall and poor cover, while temperate areas face compaction from mechanised farming and heavy machinery, which reduces macro-porosity and root penetration (10). Various management practices exist, though effectiveness differs.

Conservation tillage: It reduces crust formation by retaining residue cover, despite the fact that poorly controlled systems can result in floor sealing if residues are inadequate.

Organic amendments (e.g., compost, biochar): It improves combination balance and porosity, supplying long-term resilience in opposition to crusting. However, their adoption is restricted by the use rate and availability (11).

Cover plants: It provides shielding cover and root structures that lessen raindrop impact and decorate the soil form. Their effectiveness relies upon species preference and local climate.

Mechanical interventions (e.g., subsoiling, chiseling): It offers on-the-spot alleviation from compaction; however, they are frequently quick-lived and strength-tremendous, requiring repeated application.

Chemical conditioners: They are effective in dispersive soils susceptible to crusting, particularly in sodic environments, but much less applicable in non-saline contexts (12). Mechanical methods offer short-term correction, while biological and organic approaches build long-term resilience by improving soil structure and microbial activity (13). Integrated practices, which cover vegetation, organic amendments and minimum tillage, are more sustainable than single interventions. Compaction and crusting range through the region, requiring frameworks that provide stability, instant vs. long-term solutions, cost effectiveness and adaptability to neighbourhood agro climatic conditions.

Soil crusts and their implications for soil health

Soil crusting is a major physical degradation process that reduces infiltration, impedes seedling emergence and quickens erosion. While several varieties of crusts had been diagnosed as structural, depositional, erosional, chemical and biological, their significance lies much less in their definitions and extra of their impacts and control relevance (14).

Structural crusts

Structural crusts generally form on tilled and uncovered soils, especially beneath excessive rainfall. They are thin, however, continuous, reducing porosity and growing runoff. Their occurrence in rainfed structures makes them an important motive force of erosion in tropical and semi-arid areas.

Depositional crusts

Depositional crusts occur whilst outside materials are deposited with the aid of water flow. These are more commonplace in flood-inclined or irrigated landscapes, in which sediment hundreds regulate infiltration styles.

Erosion crusts

Erosion crusts represent the end stage of surface sealing, leaving an easy, inflexible layer that quickens soil loss. They are especially excessive in sloping lands and areas with dense vegetative cover.

Chemical crusts

Chemical crusts form in sodic or saline soils due to precipitation of salts or other compounds. These are area-unique, affecting irrigated command regions in South Asia, the Middle East and components of Australia (14).

Biological crusts

Biological crusts, in assessment, may be beneficial. It is formed with the aid of microorganisms such as cyanobacteria, lichens and mosses, they stabilise soil surfaces, reduce erosion and enhance nutrient cycling. Their characteristic is increasingly more identified in dryland healing strategies. Crust severity varies by agroclimatic context. Structural and erosion crusts dominate rainfed systems, even as chemical crusts are not uncommon in irrigated zones (15). Biological crusts, although frequently not noted, can contribute to soil stabilisation and carbon sequestration. Rather than treating crust types separately, a comparative view is needed: identifying globally harmful forms, region-specific challenges and potential opportunities (e.g., biological crusts). This underscores integrated strategies-residue cover, organic amendments and biological methods-to mitigate crusting and strengthen soil resilience (16).

Mechanisms of crust formation

Table 1 summarises key mechanisms of soil crust formation, their effects and local drivers. It highlights how raindrop impact, particle deposition, compaction, chemical dispersion and land use pressures reduce infiltration, destabilise aggregates and boost runoff. By comparing techniques and situations, it clarifies international as opposed to vicinity-precise degradation challenges (16).

Soil compaction

Soil compaction occurs when bulk density rises and porosity declines, restricting water infiltration, root growth and gas exchange. Agricultural intensification such as heavy machinery, repeated ploughing and negative moisture management has worsened the problem. Globally, compaction is a major form of physical degradation (17). Bulk density in compacted soils often exceeds

Table 1. Mechanisms and impacts of soil crust formation (16)

Mechanism	Primary impact on soil	Contribution to degradation	Key climatic/soil factors
Raindrop impact on aggregates	Breaks soil aggregates, reduces porosity	Initiates erosion, weakens structure	Intense rainfall, bare soil surfaces
Leaching and deposition of fine particles	Blocks pores, reduces infiltration	Surface sealing, higher runoff	Medium-textured soils, stormwater flow
Surface compaction	Creates a dense thin layer	Limits water entry, root penetration	Heavy machinery, repeated tillage
Chemical dispersion of clays	Disaggregates particles	Promotes crusting and salinity issues	High exchangeable sodium, sodic soils
Land use pressure	Loss of organic matter, poor structure	Accelerates degradation, erosion	Over-cultivation, arid/semi-arid regions

1.6 g/cm³, compared to the optimal 1.1–1.4 g/cm³, reducing macro-porosity by up to 50 % and lowering hydraulic conductivity and nutrient diffusion. In Europe, 32 m ha of arable land are affected, while in Sub-Saharan Africa compaction is increasingly reported in intensive maize and wheat systems (18). Soil compaction produces effects that extend below the surface layers, reducing porosity and thereby limiting root growth and microbial activity. Increased bulk density impedes downward and lateral water movement, raising risks of runoff and erosion. Altered microbial communities displace anaerobic organisms, which decreases biodiversity and weakens soil resilience. Yield losses of 10–20 % are often said, depending on severity and crop type. Management practices vary in effectiveness: organic amendments such as compost, manure and biochar improve aggregation and decrease bulk density; controlled visitors farming minimises machinery brought about compaction; and cover vegetation beautifies root penetration and porosity. While deep tillage or subsoiling provides short-term alleviation, the process is power intensive and transient. Mechanical methods offer on-the-spot correction, while natural processes build long-term resilience by restoring soil structure and microbial range. Therefore, compaction is quality managed through included strategies-herbal inputs, reduced tillage and site visitors management-adapted to local agro climatic conditions (19).

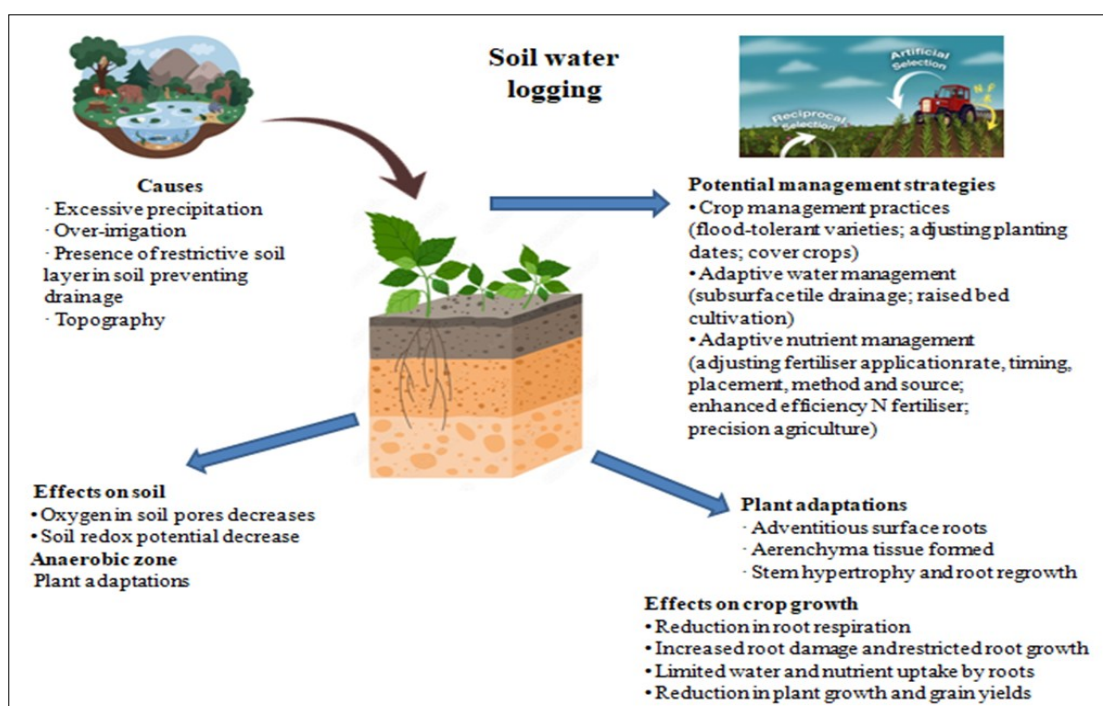
Soil desertification

Soil desertification is a primary form of land degradation, undermining food security, economies, weather balance and soil fitness. Its international significance is contemplated in the UN

Conference on Desertification (1977), the UNCCD (1994) and its inclusion in SDG 15. The term, first used by Luvauden (1927) and broadened by Aubreville (1949), refers to degradation driven by human activity and climate change in arid, semi-arid and dry sub-humid regions (20). The UN defined it as the diminution or destruction of biological potential, leading to desert-like conditions (21). Recent estimates show soil deterioration affects 1036 m ha (20.5 % of drylands), while desertification impacts 1470 m ha (29 %). In India, 82.34 m ha are affected (22). Assessment relies on global assessment of soil degradation (GLASOD) maps and expert knowledge of degradation processes. According to United Nations Environment Programme (UNEP), soil degradation is pushed via numerous reasons, consisting of climate extremes, temperature and rainfall variability, overgrazing, deforestation and unsustainable farming practices. The overuse of plant life for family and bio industrial wishes further speeds up the decline (23). These pressures lead to speedy flora loss and a decrease in soil natural carbon, while extended soil and sand movement contribute to wasteland enlargement. As soils end up greater uncovered, they grow increasingly at risk of wind and water erosion. Biological effects are also obvious, with reduced microbial diversity and populations weakening soil resilience. In addition, altered topography and changes in soil surface relief similarly compromise soil fitness and long term productiveness (24).

Water logging

Waterlogging takes place when soil pores are full of water, often due to groundwater upward thrust. India impacts 11.6 m ha, making it a

**Fig. 2.** Soil waterlogging: Its effect, causes and management practices.

primary purpose of soil deterioration. Two sorts exist: subsurface waterlogging (excess water underneath soil) and surface waterlogging (extra water above). Plant cover, rainfall and soil development strongly have an impact on its occurrence (Fig.2) (23). Waterlogging occurs under specific conditions, such as rain-prone regions, canal command areas with over-irrigation, riverbanks affected by flood expansion, low or raised terrain where water accumulates and reservoir surroundings prone to seepage. These issues are further exacerbated with the aid of soils with low infiltration capacity, the presence of hardpan layers and excessive sodium salt content. The impacts on soil health are vast: decreased warm temperature, aeration and structural stability; oxygen depletion leading to anaerobic breakdown and poisonous gasoline buildup; nutrient losses through leaching and runoff; and disrupted nutrient cycling with microbial imbalances, in which cardio organisms are replaced by using anaerobes. As a result, soil develops poor tillage characteristics and becomes unsuitable for most vegetation. Fig. 3 illustrates the impact of waterlogging on soil parameters, displaying decreased aeration, elevated bulk density and nutrient leaching. Prolonged saturation lowers microbial activity, disrupts organic decomposition and causes the accumulation of poisonous elements. These modifications weaken soil shape, reduce fertility and in the end, impair crop growth and productivity (24).

Chemical degradation of the soil

Soil chemical health is central to agricultural productiveness and environment resilience, yet its miles increasingly more compromised by way of more than one degradation strategies. Unlike physical crusting or compaction, chemical degradation without delay alters nutrient availability, soil structure and microbial interest, thereby interacting with each biological and physical dimension of soil fitness. Globally, chemical degradation manifests in numerous key forms (25):

Decline in soil organic carbon (SOC): Soil natural carbon loss reduces fertility, microbial variety and water retention. An anticipated 133 billion tons of SOC had been lost globally since the dawn of agriculture, with the highest depletion in intensively cultivated regions of Asia and Africa.

Soil acidity and sodification: Acidification is a major issue in humid tropics due to continuous fertiliser use, at the same time as sodification affects over four hundred m ha worldwide, especially in irrigated command regions of South Asia, the Middle East and Australia.

Nutrient imbalance and deficiencies: Sub-Saharan Africa faces extreme nutrient depletion, with common nutrient losses of 22 kg N, 2.5 kg P and 15 kg K per ha yearly, undermining food security.

Agrochemical accumulation: Excessive pesticide and fertiliser residues alter microbial groups and make a contribution to groundwater contamination, mainly in East Asia and Europe.

Soil pollution: Industrial and urban areas face heavy metallic contamination (e.g., cadmium, lead), which reduces crop protection and ecological integrity (26).

Table 2 provides a comparative analysis of the main types of soil chemical degradation, showing their global reach, nearby hotspots, interactions with natural and physical defences and potential mitigation techniques. It draws attention to the ways that issues such as the reduction of SOC, acidification, sodification, nutrient depletion, agrochemical accumulation and pollutants differ in intensity and geographic distribution across different countries. By synthesising numerical data and linking every degradation kind to sensible interventions, the table helps readers speedy hold close which troubles are most critical globally, which can be place-specific and how they can be addressed via agronomic or technological solutions (26).

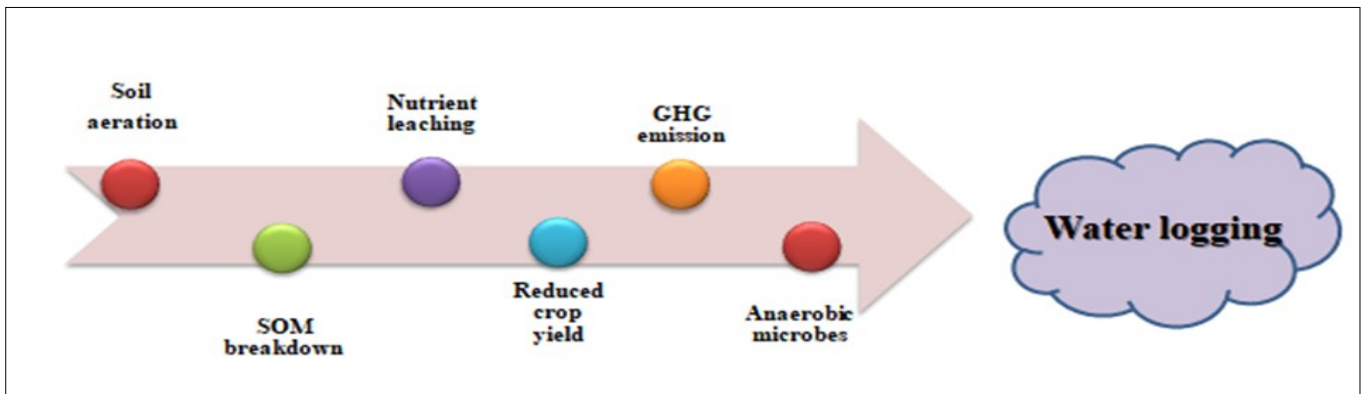


Fig. 3. Impact of waterlogging on soil parameters.

Table 2. Comparative summary of chemical degradation (26)

Type	Global extent/severity	Regional hotspots	Interactions with other degradation	Mitigation strategies
Soil organic carbon decline	133 billion tons lost	Asia, Africa	Weakens structure, reduces microbial diversity	Organic amendments, cover crops and reduced tillage
Acidification	Widespread in humid tropics	South East Asia, Latin America	Alters nutrient cycling, microbial stress	Liming, balanced fertiliser use
Sodification/salinity	400 m ha affected	South Asia, the Middle East and Australia	Promotes crusting, compaction	Gypsum, improved irrigation, salt-tolerant crops
Nutrient depletion	22–40 kg/ha annual losses	Sub-Saharan Africa	Reduces yields, microbial imbalance	Integrated nutrient management, crop diversification
Agrochemical buildup	High in intensive systems	East Asia, Europe	Pollutes soil, reduces biodiversity	Precision farming, biopesticides
Pollution (heavy metals)	Localised but severe	Industrial belts, peri-urban zones	Toxicity to plants/animals	Phytoremediation, stricter regulation

Reduction in soil organic matter

Between 1895 and 2530 Pg of carbon are found in soil, making it a significant global carbon reservoir that is three times larger than the biotic carbon pool and twice as large as atmospheric carbon. Of the full carbon in soil, 695 to 930 Pg is inorganic, while 1200 to 1600 Pg is natural. It is critical to analyse the elements that notably impact soil natural carbon, particularly in light of the marked decline in soil natural carbon in Indian soils and global agricultural structures (27). Organic carbon is more important for soil health than either of the other two components and it is essential for maintaining soil health and greatly increasing crop yields because it is both a source and a reservoir of plant nutrients.

Factors that affect the amount of organic carbon in the soil

Soil organic carbon varies with crop management and land use. Fertilisers can boost SOC, while crop increase and tillage often lessen it. At the agro surroundings level, tillage in arable plants and crop desire are the number one drivers of SOC decline (28). Conservation tillage, now extensively adopted, contrasts with conventional plow primarily based tillage, which speeds up SOC loss through residue burning, aggregate disruption, exposure to decomposition, biomass removal, reliance on inorganic fertilisers and constrained crop variety. Conservation agriculture counters those outcomes via 3 concepts: residue retention, minimum soil disturbance and crop diversification (29). Supporting practices include subsurface fertiliser placement, selective herbicides and improved nitrogen release from residues.

Fig.4 depicts the factors affecting SOC illustrates long-term experimental evidence on crop culture and fertility inputs (30). In India, trials show SOC declines with continuous cultivation but rises when chemical fertilisers are balanced with organic sources. Table3 compares conservation vs. conventional tillage. Soil organic carbon patterns differ among permanent agriculture and arable systems due to disturbance frequency, at the same time as crop species vary in carbon sequestration ability. Land use adjustments also strongly affect SOC. Converting marginal land to agriculture reduces SOC, though energy crops or agroforestry can stabilise or enhance it (31). Shifting cultivation, commonplace in northeastern India, lowers SOC with the aid of clearing the herbaceous flora before cropping.

Changes in the reactions of the soil (acidification and sulfation)

Soil interactions critically form chemical health by way of regulating nutrient availability, cation/anion exchange, base saturation, chelation and aggregation. Sodium and other minerals strongly influence soil aggregation. Soil reactions also affect the balance of nutrient bureaucracy, biogeochemical cycling and microbial roles. Crops thrive near neutral pH; deviations compromise soil chemistry (32). Due to buffering capability and mineral dominance (~45 % of soil volume), changes in soil reactions from human sports (soil, water, plant control) arise slowly. Soil pH is influenced by both environmental and human drivers that act over the years to modify its balance. Environmental factors, which include weather conditions, such as temperature and rainfall, make contributions to



Fig. 4. Factors affecting soil organic carbon (SOC).

Table 3. Distinctions between conservation and conventional tillage (31)

Particulars	Conventional tillage	Conservation tillage
Energy requirement	Higher	Lower
Cropping system	Mono-cropping of crops or single cropping system	Diversified crops and crop rotation
Nutrient management	Chemical-based nutrient management (intensive use of chemical fertilisers)	Integrated nutrient management with the inclusion of organic sources and microbes
Footprint on natural resources	Higher	Lower
Residue management	Complete removal or burning of crop residue	Maintaining at least 30 % soil surface covered with residue
Fallowing system	Ideal fallow land without any crop cover on the soil surface	Growing of cover crops
Tillage system	High intensity; plough-based tillage system	Minimum tillage or zero tillage
Soil health	Poor/degraded	Healthy soil
Sustainability	Lower	Higher

erosion and leaching, even as broader climatic impacts influence the weathering of determining material. Topography and flowers additionally play a function in regulating soil acidity and alkalinity. Human sports, in addition, accelerate pH changes through land use shifts, fertility inputs from natural and inorganic sources and the application of amendments, which include lime and gypsum. Together, those natural and anthropogenic drivers can render soil unsuitable for agriculture, with the aid of causing nutrient imbalances, toxic ion accumulation and disruptions in microbial cycles, in the end decreasing soil productivity and resilience.

Acidification: Natural and human reasons lower soil pH to unsuitable degrees. Drivers consist of acid rain, acid-producing fertilisers, nitrogen fixation, nutrient uptake, natural mineralisation and root exudates (33). Acidification alters microbial populations, reduces nutrient availability and increases root toxicity. Globally, it affects 3950 m ha of arable land; in India, 17.9 m ha are impacted.

Sodification: The contrary manner, where sodium bicarbonates/ carbonates improve soil pH. Excess salts disperse aggregates, degrade soil shape, lessen hydraulic conductivity and infiltration, modify nutrient availability and cause sodium toxicity in roots. Productivity and soil fitness decline considerably.

Modification of soil mineral nutrient status (nutrient imbalance, multi-nutrient deficiency and nutrient mining)

Nutrient application is a key input in modern agriculture, driven by declining soil fertility, stronger crop response to fertilisers and intensified cropping systems. Soil nutrient status changes through nutrient mining, multi-nutrient shortfall and nutrient imbalance (34). Multi-nutrient deficits arise from reliance on primary nutrients (N and P) and depletion of secondary/micronutrients. Imbalances occur when nutrient addition does not match crop uptake. Nutrient mining the gap between crop removal and replenishment causes a negative balance of 8–10 mt annually in Indian soils (35). Soil nutrient status is intently connected to standard soil health and agricultural productivity, with numerous key principles highlighting this relationship. Rising deficiencies in farmed soils and ranging stages of nutrient imbalance immediately affect crop overall performance, as flora respond in another way to fertiliser inputs, relying on the present situation. Recycling agricultural by means of products in place of resorting to wasteful practices, including burning, can assist repair nutrients, while the addition of natural numbers performs an

essential function in maintaining nutrient supply (36). Microbial communities, in addition, make a contribution by means of driving nutrient cycling and maintaining soil fertility. Long-term period utility of fertilisers at endorsed costs impacts soil nutrient reserves, yet excessive use of chemical fertilisers often reduces soil quality. Nutrient mining has tremendous financial and manufacturing influences, at the same time as adjustments in SOC regulate nutrient shipping capability. Neglecting soil and water conservation results in the lack of nutrient-rich topsoil and in depth cereal based totally structures or cultivation on marginal lands in addition disrupt fertility, making soils less resilient and efficient (37).

Toxic compound accumulation (Agrochemicals)

The buildup of poisonous compounds in soil in large part stems from agrochemical use. Technical grade agrochemicals in India rose from 39773 to 52980 Mt, though utilisation consistent with hectare remains lower than in wealthier countries: China 10.45 kg/ha, Japan 18.94 kg/ha, Mexico 7.87 kg/ha. Overuse of chemical salts and natural sources like sewage, sludge and nighttime soil also introduces heavy metals, degrading soil fitness. Unregulated agrochemical use mixed with restrained farmer consciousness is a prime driver of soil chemical deterioration (37). This misuse disrupts populations of soil microplant life and microfauna, alters nutrient biogeochemical cycling and reduces plant boom whilst selling the bioaccumulation of pollution in plants and animals. Although agrochemicals continue to be important for crop protection, their use ought to follow rules and exceptional practices to decrease dangerous accumulation and protect long-term soil health.

Soil pollution

Soil contamination in farmed areas is a growing consequence of agrochemical-based agriculture and poor management. Soil pollution is defined as physical, chemical, biological, or radiological alteration of the soil surface caused by accumulation of natural or synthetic materials that disrupt ecological balance and self-cleaning capacity (Fig. 5). Soil contamination arises from several major sources, along with the misuse of agrochemicals, fertilisers and herbicides, especially phosphatic inputs, along with pollutant-rich materials and business waste. Inferior plastic films, infected irrigation water, farming close to municipal dumps and incorrect disposal of industrial waste further make a contribution to the hassle. Seepage from landfills, the absence of soil biota for agrochemical breakdown

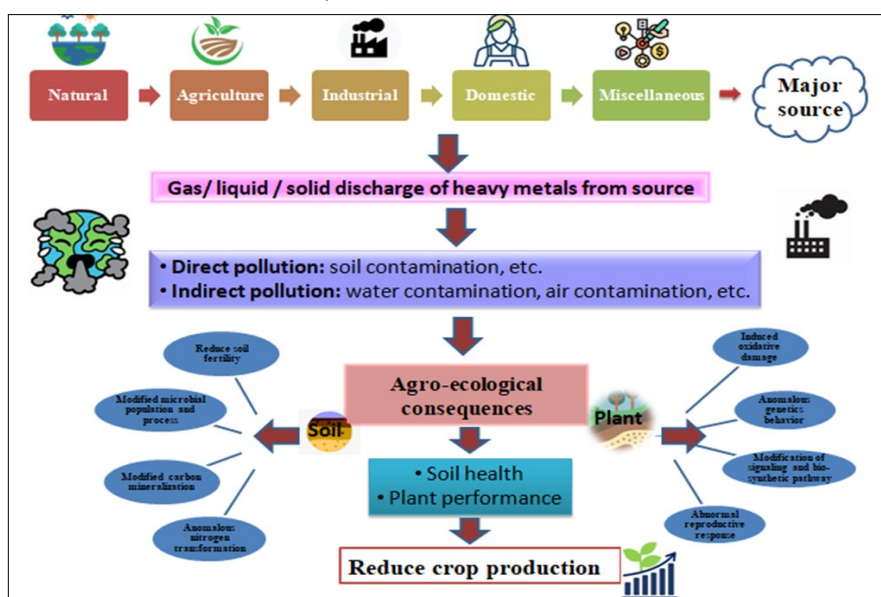


Fig. 5. Soil pollution and agrochemical accumulation.

Table 4. Comparative summary of biological degradation (35)

Issue	Cause	Impact on soil & crops	Mitigation approach
Loss of microbial diversity	Intensive tillage, chemical overuse	Reduced nutrient cycling, poor resilience	Organic matter addition, crop diversification
Decline in viable microbial counts	Continuous monocropping, residue removal	Lower soil respiration, enzyme activity	Biofertilisers, compost, cover crops
Pathogen proliferation	Imbalanced microbial communities	Increased disease incidence, yield loss	Biocontrol agents, crop rotation
Accumulation of harmful substances	Agrochemical residues, pollution	Toxicity, slowed organic breakdown	Precision farming, reduced chemical inputs
Disrupted soil functions	Combined physical & chemical stress	Weak nutrient cycling, poor organic matter turnover	Integrated soil management

and forget about of cleanup measures exacerbate contamination and accelerate soil decline. The results of these practices are an extensive range (38). Soil residences are altered through nutrient toxicity, salinity, modifications in porosity and reactivity. Heavy metals gather in soils, entering the food chain and posing long-term health dangers. Leaching procedures contaminate both surface and groundwater, detrimental to aquatic ecosystems and decreasing water quality. Crop germination and boom are impaired, even as microbial populations and nutrient cycling are disrupted. In excessive instances, soils end up unsuitable for cultivation. Because heavy metals cannot be degraded biologically or bodily, they persist for long intervals, growing boundaries to using nutrient-rich minerals in natural farming and undermining sustainable agricultural practices.

Soil biological degradation

Biological soil properties often receive the least attention, yet modern farming has significantly disrupted them. Loss or reduction of microbial populations alters ecosystem biochemical processes. Microbial traits are now studied at the rhizosphere and genomics level due to their critical role in soil functions (39). Fig.6 shows how causes (loss of diversity, pathogen rise, harmful substance buildup) lead to effects (disrupted nutrient cycling, reduced respiration, poor organic matter breakdown), resulting in consequences (lower productivity, soil vulnerability). Interventions-biofertilisers, organic matter, crop diversification-help restore soil functions. Biological deterioration of soil is indicated by abnormal viable counts, reduced species diversity and distribution, disrupted nutrient cycling, respiration and enzyme activity, harmful substance buildup due to slow breakdown and increased pathogen proliferation leading to disease spread. Assessing these indicators is challenging because of complex plant-microbe interactions, the high adaptability of microbes to management changes, the difficulty of identifying diverse microbial communities and their sensitivity to soil changes, which often makes them reliable only for short-term assessment. Table 4 shows the comparative summary highlights how biological degradation reduces productivity by weakening microbial diversity, lowering viable counts and disrupting nutrient cycling. Pathogen growth and harmful substance accumulation intensify crop losses. These issues interact with chemical and bodily degradation, decreasing resilience. Integrated interventions, biofertilisers, organic and crop diversification-provide sustainable recovery.

Soil ecosystem services

Continuous human activity drives bodily degradation approaches that adjust soil surroundings offerings, leading to slower contaminant breakdown, decreased nutrient shipping, lack of soil natural carbon and carbon sink potential, shifts in microbial diversity, growth of salt-affected soils and a typical decline in soil

carrying capability. Research on soil ecosystem services is vital as human impacts intensify, resource depletion accelerates and climate change raises concerns over soil functions and growing populations and livestock increase pressure, while global economic models often prioritise growth over ecological sustainability (40).

Effect of degrading soil on plant development

Soil degradation undermines plant growth by lowering productivity, profitability and resilience. Its severity varies by type, but combined impacts on yields are significant. Physical degradation (erosion, compaction, crusting) is globally most excessive. Erosion alone eliminates 24 billion lots of fertile soil annually, reducing yields in rainfed systems throughout Africa, South Asia and Latin America. In the EU, 12 m ha of degraded land results in losses of 155 m in gross domestic product (GDP) and 300 m in agricultural output (40). Chemical degradation (salinity, sodicity, nutrient depletion and aluminum toxicity) is vicinity-specific, however, similarly unfavourable. In India, erosion and chemical constraints value US\$1-6 billion annually. In Sub Saharan Africa, nutrient depletion and salinity affect 23 m ha of cropland, reducing yields of maize, sorghum and millet. These constraints lessen nutrient availability, impair root function and heighten dependence on external inputs. Biological degradation, less studied but critical, reduces microbial diversity, disrupting nutrient cycling and disease suppression. Pathogen proliferation lowers germination and crop establishment (41). Cyanobacteria-dominated crusts, for example, reduce grass germination, directly harming pasture productivity (41).

Integrated impacts

The combined effects of physical, chemical and biological degradation are more severe than individual processes. For example, sodicity (chemical) promotes crusting (physical), which reduces microbial variety (biological). These remarks loops boost up soil decline, enlarge yield losses and make soils much less responsive to conventional amendments (42). Physical degradation is the maximum full-size driving force of yield loss, while chemical constraints generally tend to dominate irrigated and intensively farmed areas. Biological degradation further limits long-term resilience by weakening crucial soil functions, making incorporated control vital for sustaining productivity. Table 5 shows the comparative summary suggests how degradation reduces water and nutrient use performance. Salinity increases water demand and lowers productivity; nutrient inefficiency limits restoration despite fertiliser inputs; organic degradation further weakens resilience. Integrated strategies, such as micro irrigation, gypsum, organic amendments and bio-fertilisers are vital to improve efficiency and sustain yields (43). Mitigation of soil degradation requires integrated techniques. Conservation agriculture with decreased tillage and residue retention allows manage erosion and compaction. Organic

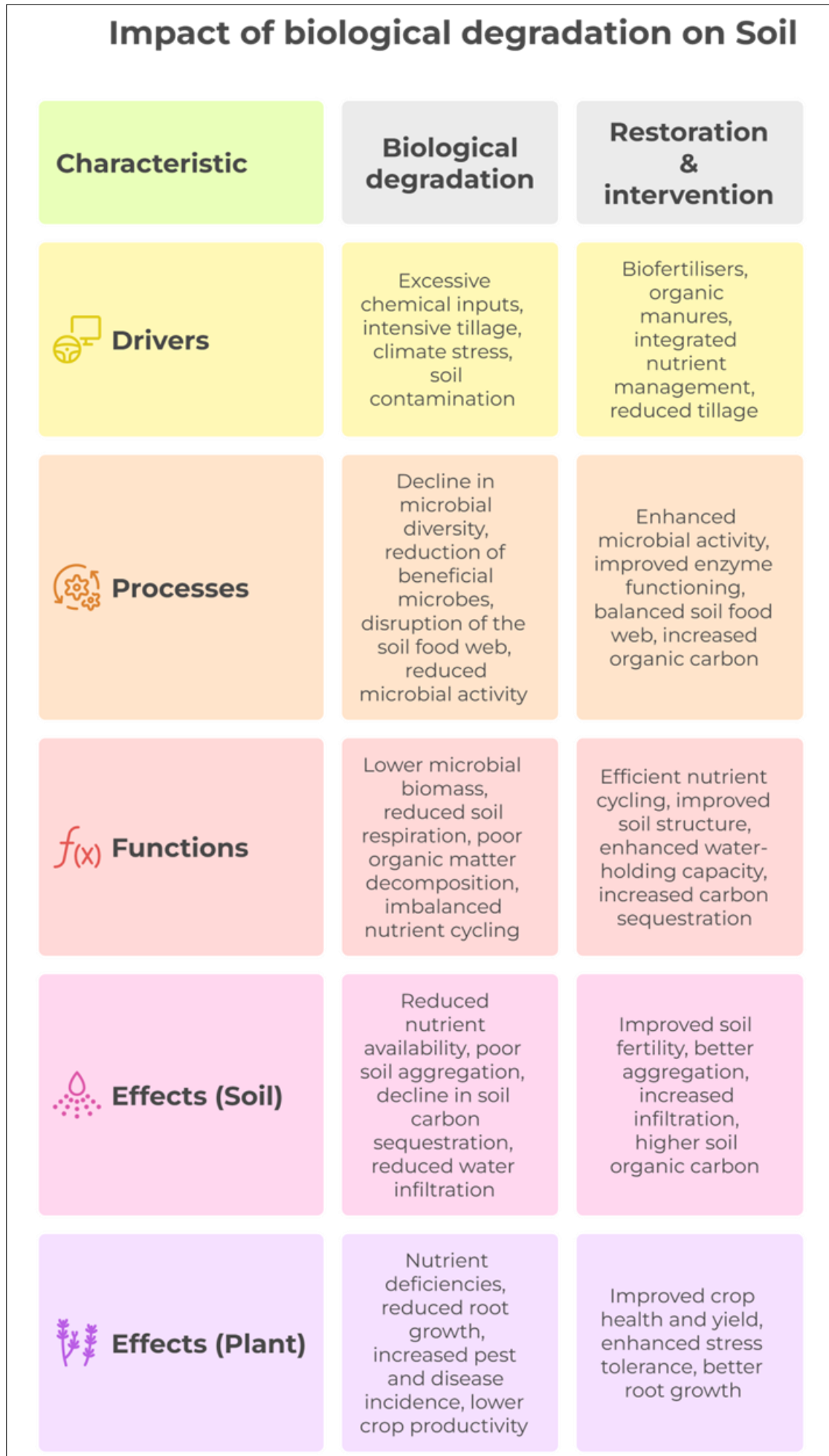


Fig. 6. Flowchart of biological degradation pathways and restoration in soil.

Table 5. Comparative summary of water and nutrient use efficiency (WUE and NUE) under soil degradation (42)

Constraint	Observed data	Impact on productivity	Mitigation strategies
Salinity (irrigation command areas)	Border irrigation WUE: 1.36 kg/m ³ ; Basin irrigation WUE: 1.04 kg/m ³ ; Drip irrigation with saline water: 21.45 kg/m ³ vs control 39.2 kg/m ³	Higher water demand, reduced crop yields (e.g., watermelon, rice)	Micro-irrigation, gypsum application, salt-tolerant crops
Nutrient inefficiency (saline-sodic soils)	N use efficiency improved with 100 kg N/ha + 50 % gypsum; Agronomic efficiency highest at 130 kg N/ha + 100 % gypsum	Reduced nutrient recovery, higher fertiliser demand	Integrated nutrient management, green manure (Sesbania), farmyard manure
Biological degradation (pathogens, pests)	Global yield losses (2001–2003): wheat 28.2 %, rice 37.4 %, maize 31.2 %, potatoes 40.3 %, soybeans 26.3 %, cotton 28.8 %	Reduced the effectiveness of water and nutrient inputs due to disease pressure	Crop diversification, biocontrol agents and reduced chemical residues
Regional examples	India: annual land degradation cost US\$1–6 billion; pest losses: cotton 30 %, rice 25 %, oilseed 20 %, pulses 15 %, groundnut 15 %, wheat 5 %	Economic losses, reduced food security	Soil health cards, precision farming and integrated pest management

amendments and crop diversification restore nutrient stability and microbial range, while bio-fertilisers and inoculants rebuild organic fitness. Precision farming and soil fitness playing cards further support tracking and management, making sure long time soil sustainability. Table 6 shows the effects of soil degradation on major crops highlights impacts on profitability, productiveness and crop responses to amendments (43). Studies verify huge consequences of physical and chemical degradation on soil health, while organic degradation reduces grass germination because of cyanobacteria-dominated crusts.

Novel agronomic and innovative soil management approaches for improving soil health

Diversification of nutrient sources

Soil nutrients are furnished naturally or through external inputs such as organic, inorganic and microbial inoculants, each influencing soil fitness definitely or negatively. Chemical fertilisers, although widely used for their fast response, ease of application, low price and instant yield gains, frequently cause soil degradation, nutrient imbalances and multi-nutrient deficiencies when applied repeatedly (44). Their dominance in subsequent years is reinforced by the inability of other sources to fully meet crop demands, intensification of farming systems and declining availability of alternatives. Because nutrients from chemical fertilisers are short-lived and prone to leaching, uneven use and neglect of micronutrients like Fe and Zn, as well as secondary nutrients such as S, further exacerbate soil deterioration.

To improve sustainability, fertiliser sources should be diversified to provide a range of nutrients, enhance soil properties and reduce environmental impact. Partial substitution with on-farm or affordable off-farm resources such as agro-industrial wastes, unprocessed minerals, green and brown manures, weed manures and biofertilisers can strengthen crop nutrition and preserve soil health (45). However, the provision of sponsored chemical fertilisers, their strong, quick-term productivity gains and constrained organic sources restrict diversification (46). Regionally, chemical fertilisers continue to be dominant in Asia because of subsidies, while organic amendments are more common in Africa and Latin America, providing slight yield responses, however, enhancing microbial diversity and resilience (47). Agro-industrial wastes and minerals, together with sugarcane biogases and rock phosphate, provide region-specific benefits with the aid of recycling nutrients and reducing waste. Biofertilisers and microbial inoculants, more and more followed in Europe and North America with coverage aid, make a contribution to nutrient cycling and disease suppression in spite of variable yield outcomes. Overall, even as chemical fertilisers continue to dominate because of immediate yield profits, diversification through natural, commercial and microbial resources is crucial to stability, brief-term productivity with long-term soil health. Regional techniques should emphasise fee powerful, locally available sources while regularly decreasing dependence on chemical fertilisers to make sure economic viability and environmental sustainability (48).

Table 6. Effects of soil degradation on major crops (43)

Crop	Soil degradation problem	Effect	Correction measure
Wheat	Salinity due to irrigation water	Reduction in grain and straw yield, harvest index and growth parameters	Use of <i>Azospirillum</i> sp. from saline soil
Rice bean	Soil acidity	Reduction in growth, yield and economic parameters	Use of lime at 0.6 t/ha
Rice	Acid sulphate soil & aluminum toxicity	Lower rice yield; reduced exchangeable cations	Magnesium limestone, sugarcane organic fertilisers
Chickpea	Sodium salt sensitivity	Affects vegetative/reproductive growth; podding stage sensitive	Application of wood biochar
Red gram + Groundnut	Soil salinity & poor fertility	Lower yield, shelling %, oil content and protein %	Application of paper mill sludge, farmyard manure and nutrients
French bean	Nutrient deficiency in acidic soil	Poor growth and yield attributes	Use of recommended nutrients + boron
Garden pea	Soil acidity	Adverse impact on growth and soil properties	Biochar application (corn or <i>Lantana camara</i>)
Rice–wheat system	Soil compaction	Poor root growth: reduced root mass, length and primary roots	Conservation agriculture practices
Rice–maize system	Nutrient mining (Potassium)	Exchangeable K reduced by 5 mg/kg soil	Potassium application increases rice yield by 1.8 t/ha
Rice	Sodic soil	Negative effect on plant growth and yield	Application of gypsum at 9.5 t/ha + irrigation every 4 days

Brown and green fertilisers

Green manuring, which includes cultivating leguminous vegetation and incorporating it into the soil for the duration of blooming and brown manuring, which co-cultivates *Sesbania* with rice and terminates it mid-season using herbicide, are both diagnosed for enhancing SOC, improving nitrogen availability, suppressing weeds and decreasing dependence on synthetic fertilisers. Green manuring is more common in irrigated rice structures, whilst brown manuring is extensively practiced in upland rice because of its weed management benefits (49). Despite these benefits, adoption remains constrained due to practical constraints. In rainfed agriculture, low soil moisture often hinders decomposition and nitrogen release, decreasing effectiveness; farmers in semi-arid India, for instance, record negative nitrogen restoration from green manure crops throughout drought years. High seed fees, phosphorus fertiliser requirements for legume establishment and exertions for incorporation similarly discourage smallholders, while brown manuring adds fees through herbicide costs and the need for well-timed software (50). Integration into numerous cropping structures gives answers: in rice–wheat rotations, *Sesbania* may be grown at some point of fallow periods to replenish nitrogen; in maize based totally systems, brown manuring helps suppress weeds and reduce herbicide dependence. In natural farming, which is expanding swiftly in India, green manures are an increasing number of valued as sustainable nutrient resources. Supplementing these practices with agro-industrial residues and compost can create more diverse nutrient strategies. Nonetheless, these economic and logistical drawbacks explain why farmers have not widely adopted green or brown manuring despite their proven benefits. As Table 7 shows, the effects of green and brown manuring on soil health (selected crops) (50).

Utilisation of agro-industrial waste and crop residue

Most of the gross cropped area in agriculture is devoted to arable crops, which generate large amounts of residues that are rich in organic carbon and have significant potential for nutrient diversification. Major cereals such as rice, wheat, maize, barley, sugarcane and soybeans together produce nearly 3.7–3.8 Pg of residues annually, yet a large portion of this biomass is either wasted, mismanaged, or burned, contributing to pollution and environmental degradation (51). These residues, if well utilised, can lessen dependence on chemical fertilisers, enhance soil fertility and beautify microbial variety. However, demanding situations remain: cereal residues regularly have a high C:N ratio, leading to nitrogen immobilisation and slower decomposition; they will additionally harbour pests and sicknesses, posing risks for next plants (52).

To deal with these troubles, strategies inclusive of blending residues with nitrogen-rich substances, composting, microbial inoculation, pelletisation, briquetting and biochar production can accelerate decomposition, lessen pathogen masses and enhance ease of shipping and application. Agro-industrial wastes, including pressmud, molasses, bagasse, rice and wheat milling byproducts, fruit and vegetable processing residues and oil extraction wastes, also represent valuable resources, though their use is limited by contamination risks, competing applications and logistical difficulties (53). Pretreatment strategies like drying, pathogen screening and co-composting are crucial to make those wastes safe and powerful as nutrient assets. At the farm and community level, mechanised residue incorporation using satisfied seeders and zero-till drills can maintain residues *in situ*, reducing air pollution from burning and enhancing soil natural fertility. Community composting gadgets and biogas flora can handle massive volumes of residues, converting waste into nutrient-rich amendments and renewable energy. Policy aid for logistics, residue collection and cooperative processing facilities can lower prices and make residue utilisation more accessible to smallholders. Integrating legumes into cereal-based totally systems improves nitrogen balance, at the same time as adjusting nutrient control to account for decomposition requirements guarantees better synchronisation of nutrient release with crop demand. In natural farming, where off-farm inputs are expensive, in-situ residue management gives an extra within your budget and a sustainable alternative (54). Overall, crop residues and agro-business wastes represent a massive, underutilised resource that, while controlled efficaciously, can diversify nutrient resources, toughen soil fitness, lessen environmental pollution and sell long-time period agricultural sustainability. Agro-business wastes and crop residues notably improve soil health via enriching organic carbon, which helps fertility, microbial diversity and sustainability. These residues beautify useful microorganisms by way of supplying meals and energy; improve soil aggregation and infiltration and chemically buffer pH, growth cation exchange capability, increase base saturation and aid micronutrient chelation (55). They also assist destroy down contaminants, strengthening soil resilience and productivity. Major cereals like rice, wheat, maize, barley, sugarcane and soybeans generate 3.7–3.8 Pg of residues annually, presenting a sizeable but underutilised resource. Safe utilisation calls for composting, microbial inoculation, co-composting, pelletisation, briquetting, or biochar production to address high C:N ratios and pathogen dangers. Agro-commercial byproducts such as pressmud, molasses and bagasse need pretreatment before use (56). Large-scale answers consist of mechanised residue incorporation,

Table 7. Effects of green and brown manuring on soil health in selected crops (50)

Crop/cropping system	Practice description	Impact on soil health
Maize	Green manuring with <i>Orychophragmus violaceus</i> + 100 %, 85 %, 75 % of the recommended NPK	Increases the amount of microbial biomass N, dissolved organic N and mineral N in surface soil by adding 21.5–94 kg N, 2.2–9.8 kg P and 21.2–99.2 kg K/ha
Rice–rice cropping system	Green manuring crops grown in fallow or intercropped (4:1 ratio)	SOC, fulvic acid and humic acid gradually accumulate
Rice	Green manuring with <i>S. aculeata</i> and <i>Crotalaria juncea</i>	Enhancement of soil organic carbon and N and P availability
Rice–wheat cropping system	Incorporation of green manure crops before puddling	Improved infiltration, decreased bulk density, higher hydraulic conductivity, improved soil aggregation and decreased soil strength
Rice	Direct-seeded aerobic rice + brown manuring of <i>Sesbania</i> + no-till wheat	Increased soil N and organic matter; better root length density; decreased bulk density (0.03–0.09 Mg/m ³)
Rice–mustard cropping system	Zero till DSR + brown manuring + zero till mustard with residue retention	Improved hydraulic conductivity, pH, total N, P and K; higher soil quality index (SQI) in comparison to traditional methods

community composting, biogas flowers and supportive policies to lessen fees and pollution. Integrating legumes into cereal structures and optimising nutrient control in addition complements efficiency, while in-situ residue use gives a sustainable, most economical opportunity to expensive external natural inputs (57).

Utilisation of minerals and waste minerals

Limited micronutrient availability is a primary challenge in organic farming, where nutrient delivery relies upon soil natural matter, manures and crop residues. Mineral-based assets like rock mineral flour (RMF) release vitamins slowly but sustainably, making them suitable for lengthy-period vegetation and soils with low buffering potential. A 140-day look at confirmed RMF released 4.6 % Cu and 5.8–15.5 % Zn, sufficient to satisfy cereal crop needs, although less immediate than artificial fertilisers. Mineral amendments are simplest in acidic, weathered, or coarse-textured soils, enhancing long-term fertility. Crops, along with cereals, millets, oilseeds and perennials, benefit most from gradual-release nutrition, not like greens that call for fast nutrient supply (58). In herbal and low-enter farming structures, minerals are an increasing number of getting used as pesticide-free nutrient assets for numerous reasons. Organic nutrient inputs by myself are often insufficient to meet contemporary crop necessities, making mineral supplementation necessary. The identification of microbial methods and using precise inoculants can similarly decorate mineral solubilisation and nutrient availability. Additionally, huge amounts of mineral waste generated with the aid of processing industries present disposal demanding situations; however additionally create possibilities for agricultural reuse. Rising charges and import dependency linked to chemical fertiliser manufacturing spotlight the need for alternative nutrient resources, while sure uncooked minerals, even though uneconomical to process into fertilisers, may be directly applied under suitable soil conditions to help crop growth (59).

Despite their blessings, the use of mineral wastes in agriculture faces boundaries together with heavy metal content, logistical difficulties in transporting bulky materials and confined information of soil-crop-microbe interactions that govern nutrient release. However, their low nutrient concentration, slow-launch behaviour, decreased hazard of non-point source pollution and cost-effectiveness, especially in by-products like primary slag and phosphogypsum, make them valuable supplementary and complementary nutrient assets in organic and sustainable farming structures. From a soil health attitude, mineral amendments decorate the soils' inherent nutrient-imparting potential by improving mineral stability, reinforcing biogeochemical nutrient cycling through numerous and lively microbial communities and helping mitigate soil structural and biological degradation as a result of extended chemical fertiliser use (60).

Weeds as fertilisers

Weeds, even though classified as undesirable plant life and a form of biotic strain, may be effectively utilised as organic manure when managed correctly. Several weed species possess higher concentrations of macro- and micronutrients than many cultivated crops, making them a valuable supplementary nutrient source in sustainable and organic farming structures. However, their powerful use calls for careful consideration of species choice, timing of incorporation and management practices (61).

Guidelines for weed species selection

Not all weeds are suitable for use as manure and careful selection is

necessary to ensure positive effects on soil and crops. Preference should be given to fast-growing, non-allopathic species with high biomass and nutrient content, such as *Amaranthus* spp., *Chenopodium* spp. and *Parthenium hysterophorus*, before flowering. Weeds should be collected before seed formation to prevent future infestations and species with soft tissues and low lignin content are ideal since they decompose quickly and enhance nutrient mineralisation. Locally abundant weed flora are preferable to reduce collection and transportation costs. In contrast, allelopathic weeds and those that harbour pests or pathogens should be avoided, as their residues may suppress crop growth during decomposition (62).

Optimal timing and method of application

Not all weeds are appropriate for use as manure, so careful selection is crucial to ensure wonderful effects on soil and crop growth. The only choices are speedy-growing, non-allopathic species with excessive biomass and nutrient content, including *Amaranthus* spp., *Chenopodium* spp. and *P. hysterophorus* accumulated before flowering. Weeds ought to be harvested previous to seed formation to prevent future infestations and people with smooth tissues and coffee lignin content are desired because they decompose unexpectedly and enhance nutrient mineralisation. Locally considerable weed species are also tremendous, as they decrease series and transportation prices. Conversely, allelopathic weeds and those that harbour pests or pathogens have to be avoided, on the grounds that their residues can also suppress crop growth during decomposition (63).

Impact on crop yield and soil health

Incorporating weed biomass into soil has been shown to improve physical, chemical and biological properties, just like different natural amendments. Field studies highlight advantages such as stepped forward soil moisture conservation, reduced topsoil erosion during fallow periods, extended soil natural carbon, extra microbial interest and better nutrient availability, all of which make contributions to better fertility. This practice additionally helps higher crop yields, specifically in cereals and pulses, via slow nutrient release and advanced soil structure, even as decreasing reliance on external nutrient inputs and sells cost-effective nutrient recycling. Weed-derived organic matter further improves soil aggregation, nutrient-use performance and enables the mitigation of degradation resulting from continuous chemical fertiliser use. However, mistaken management can lead to nutrient competition, allelopathic consequences, or weed proliferation, making cautious species selection and proper timing of application critical (64).

Adaptation of modern tillage system (minimum/zero tillage, stubble mulch tillage)

Conventional ploughing alters soils physical, chemical and biological properties, specifically for weed management and seedbed instruction; however, present-day herbicides and technology have shifted cognizance toward conservation tillage. Systems like low tillage, zero tillage and stubble mulch tillage lessen erosion, save time, control residues and enhance soil quality whilst presenting monetary benefits. Conservation tillage enhances soil health by way of growing organic carbon, microbial range, nutrient cycling and physical developments, which include aggregation, porosity and water-retaining potential (65). Residue retention regulates pH, conserves nutrients, reduces evaporation and helps manipulate salinity. Challenges include competing residue uses, nitrogen immobilisation, pest and pathogen risks, termite buildup and difficulties in manure or fertiliser application. Incorporating

diverse crops, especially legumes and grasses, further restores fertility and balances nutrient extraction, making conservation tillage a sustainable and resilient soil management practice. Conventional ploughing harms soil health by causing structural damage, organic carbon loss, erosion and reduced biological activity. Conservation tillage methods such as minimal, zero and stubble mulch tillage offer sustainable alternatives, improving SOC (10–30 %), aggregation, porosity, infiltration and microbial activity while reducing erosion (30–70 %). Though yields may initially remain stable or slightly lower, long-term adoption often results in equal or higher productivity, especially in rainfed systems. Residue retention with at least 30 % cover helps regulate soil temperature, reduce evaporation and enhance nutrient cycling (66). Affordable practices like mulching, partial residue incorporation and zero-till drills make adoption feasible, while supplementary nitrogen mitigates nutrient immobilisation. Widespread use requires farmer training, demonstrations and extension support, making conservation tillage a climate-resilient, cost-effective approach to improving soil health and sustaining crop yields.

Utilising biocontrol agents and plant growth promoting rhizobacteria to increase microbial diversity in the soil

Soil microbial diversity can be greater through direct and indirect techniques that complement each other. Direct techniques contain biofertilisers introducing beneficial microbes for nitrogen fixation, nutrient solubilisation, pathogen suppression, natural residue decomposition and contaminant breakdown, enhancing nutrient cycling and reducing dependence on chemical substances. Indirect strategies focus on creating favourable soil situations by way of the usage of organic inputs, decreasing chemical fertilisers, adopting conservation tillage, maintaining close to-neutral pH and diversifying crops. Legumes and forage plants like berseem and Napier grass enhance the rhizosphere with root exudates and biomass, boosting microbial abundance, productivity and common soil fitness. Indirect strategies like residue retention, mulching, manuring and progressive irrigation create favourable soil situations that enhance microbial variety, nutrient cycling, pathogen suppression and reduce reliance on agrochemicals. However, huge-scale adoption faces demanding situations: direct inoculation often offers inconsistent returns, effectiveness depends on soil and weather and microbial populations are sensitive to agrochemicals. Indirect strategies are more sustainable but incur higher initial costs, offer better preliminary costs, have advantages in terms of being behind schedule and introduce management complexity. Limited farmer focus and technical assistance similarly restrict adoption, making training, web page-unique steering and monetary incentives essential for figuring out the whole capacity of microbial range-primarily based soil health control (67).

Positive effects of microbial enhancement on soil health

Increasing microbial diversity and diversifying nutrient sources work hand in hand to improve soil health, as crop residues provide a foundation for microbial activity while microorganisms drive nutrient breakdown and turnover. Greater microbial diversity accelerates the decomposition of agrochemicals and toxic plant secretions, thereby reducing soil pollution. It also aids nutrient immobilisation, quickly storing plant vitamins to reduce losses and suppresses soil-borne pathogens through competition and opposed interactions. Additionally, microbial diversity enhances soil chemical fitness through increasing the proportion of fixed nutrient storage, particularly phosphorus, which often remains certain within the soil

and has low usage performance from soluble fertilisers. Together, those techniques enhance nutrient biking, soil fertility and long-term sustainability (68).

Efficient resource cycling through an integrated farming system

Doubling the earnings of Indian farmers requires multiple interventions with emphasis on fee reduction, efficient and useful resource use and on-farm recycling. Integrated farming systems, combining crop production with allied businesses including farm animals, roosters, composting and power technology, provide a sensible framework via recycling farm-derived resources, lowering outside input dependence, enhancing soil fertility and enhancing profitability with low funding. Evidence suggests IFS improves nutrient biking and soil fertility: recycling crop residues and animal wastes via composting and vermicomposting recovers 60–80 % nitrogen, 78.5 % phosphorus and 80–90 % potassium, in any other case misplaced via burning or disposal. Integration of poultry and small ruminants adds nutrient-wealthy manure, raising SOC via 0.2–0.4 % annually and boosting microbial activity and nutrient mineralisation. Biogas slurry utility materials 20–30 % greater nitrogen than raw farmyard manure at the same time as reducing methane emissions, making IFS cost-effective and environmentally sustainable (69).

Research indicates that IFS supply robust economic and environmental advantages via aid recycling. On smallholder farms, including fowl and vermicomposting devices, reduces fertiliser fees by using 20–40 % and raises internet farm profits by using 15–35 %. Biogas units provide renewable electricity and nutrient-rich slurry, enhancing cereal and vegetable yields by 10–25 %. Incorporating leguminous inexperienced manures like *Leucaena leucocephala* and *Gliricidia sepium* materials 50–100 kg N/ha, lowering chemical nitrogen demands. From a soil health attitude, IFS complements nutrient cycling, reduces waste and reuses residues for vermicomposting, mushroom cultivation, or animal feed, maintaining nutrient flow throughout cycles. Plant-cattle-microbial interactions create semi-closed nutrient loops that improve soil shape, microbial range and long-term resilience. Challenges include small landholdings, advertising and marketing troubles, restricted farmer awareness and capital constraints, but with education, extension help and coverage incentives, IFS adoption can reap high recycling performance, better nutrient-use performance and considerable economic gains (70).

Improvement of soil health in problematic soil through the application of soil amendments, crop cultivation practices and phytoremediation

In India, the most elaborate soil types are acidic and salt-affected soils, which cover an area of 15.93 m ha and 6.73 m ha, respectively. Globally, however, saline soil is located in 0.34 billion ha, whereas sodic soil is found in 0.56 billion ha. Soil contamination is due to sewage water, rubbish from landfills, untreated commercial effluents and seepage of commercial contaminants. Due to some of the problems, those soils require specialised control techniques and input additions, in addition to standard management strategies, in an effort to produce effective vegetation. The following is a trendy division of these practices (71).

Use of soil amendments and their effect on soil health

The major purpose of soil amendments is to repair soil fitness through correcting harmful reactions and optimising physicochemical properties for crop growth. Problem soils are

categorised as saline, sodic and saline-sodic primarily based on electrical conductivity (EC), exchangeable sodium percentage (ESP) and salt composition, every requiring specific control. In saline soils ruled by means of sodium chloride and sodium sulphate, crop growth is restrained mainly through osmotic pressure. Studies show that leaching with accurate-first-class irrigation water can reduce EC by 40–70 %, enhancing crop establishment and yield. Gypsum or iron pyrite, mixed with the right drainage, in addition useful resource for salt displacement. Saline soils are not unusual in arid and semi-arid regions such as Rajasthan, Haryana and coastal belts, in which salt-tolerant plants like barley, cotton and mustard respond nicely to leaching-based reclamation. Sodic soils, ruled by sodium carbonate with high ESP and alkaline pH (>8.5), face extreme structural degradation, negative infiltration and aeration. Applying calcium-based amendments, which include gypsum, phosphogypsum, iron sulphate, sulphur, or pyrite, reduces ESP by 20–50 %, improves aggregation and increases infiltration by 2–4 times as compared to untreated soils. In the Indo-Gangetic plains, gypsum use has boosted rice–wheat yields by means of 15–30 % via changing sodium with calcium and restoring soil structure. Saline–sodic soils, with each high EC and ESP, require integrated chemical amendments and leaching; gypsum plus leaching lowers EC by 30–60 % and ESP by 25–55 %, improving permeability and nutrient availability. Acidic soils in excessive-rainfall areas (Japanese India, northeastern hills, Southern India) benefit from liming, which increases pH from <5.5 to near-neutral, increases phosphorus availability by 20–40 %, enhances calcium and magnesium supply and decreases poisonous Al, Fe and Mn. Limed soils additionally show higher microbial biomass and enzyme activity, improving nutrient cycling and productivity, particularly in legumes and cereals. Region-precise techniques are crucial: gypsum and sulphur for sodic soils within the Indo-Gangetic plains, dolomite and simple slag for acidic soils in eastern and southern India and leaching with salt-tolerant vegetation for saline coastal regions. Tailored amendments make certain green resource use, more potent soil resilience and sustainable crop production (72).

Methods of cultivation

Cultivation techniques are also said to help manage troublesome soil, in addition to the use of soil additives. They are as follows (73):

Tillage of the soil: The following changes are recommended: opening a dead furrow, which serves as a drainage channel during an event of heavy rainfall and stores moisture; compartmental bunding, which extends the opportunity time for infiltration of rainwater; and deep ploughing, which increases infiltration of rainfall moisture to a considerable depth.

Configuration of the land: For effective crop cultivation in troublesome soils, it is also advised to level the field, which lessens depression regions where water collects and salts may build up and to plant crops $\frac{3}{4}$ high on ridges, among other land layouts.

Crop selection, irrigation and mulching

For sodic/alkali soil, Kamal grass, para grass, Rhodes grass, rice, sugar beet and green manure crops like dhaincha (*Sesbania aculeata*) are recommended; for saline soil, crops like mustard, barley, cotton and sugar beet are recommended. Additional advocated moves include the use of a certain amount of water at some point of pre-sowing irrigation to leach salts, watering frequently and shallowly, the usage of sparkling, wonderful irrigation water and the use of organic mulches to limit evaporation losses, in

order to reduce the upward migration of salts. All of these cultivation techniques beautify the bodily traits of the soil and help the variety and wide variety of soil microbes, each of which sooner or later increases soil fitness. The addition of natural depend added approximately by using crop growth, mulching and irrigation creates the right microclimate that will increase the microbial population and complements the organic health of the soil (74).

Phytoremediation

Phytoremediation is a reasonably-priced and environmentally sustainable method that uses higher plants to repair soils and groundwater contaminated with natural pollutants and hazardous metals. By employing mechanisms consisting of phytoextraction, phytostabilisation, phytodegradation and phytovolatilisation, phytoremediation reduces contaminant loads whilst concurrently improving soil fitness. This approach is specifically relevant for agricultural lands exposed to sewage wastewater, business effluents, landfill-derived composts and excessive agrochemical inputs, all of which can be increasingly more common in peri-urban and intensively farmed areas. Phytoremediation has proven a successful application throughout India, with *Brassica juncea* and *Helianthus annuus* reducing lead, cadmium and chromium ranges by 30–60 % in peri-urban soils irrigated with wastewater over 3–5 cropping cycles (75). In India, vetiver grass (*Vetiveria zizanioides*) stabilise metals in industrially contaminated soils, at the same time as species like *Sesbania*, *Populus* and *Eucalyptus* in southern and western areas immobilise contaminants close to waste sites and canals, highlighting adaptability to various agroecological situations. Long-term period studies file 15–35 % increases in soil natural carbon, 20–40 % improvements in aggregation and infiltration and more desirable microbial biomass and enzymatic activity after repeated phytoremediation cycles. Reduced metallic bioavailability improves nutrient uptake and supports safer crop production, with slow yield recuperation in contaminated soils. As reliance on agrochemicals, waste disposal and wastewater reuse grows, soil contamination is predicted to pressure degradation. Integrating phytoremediation into farming structures gives a low-cost, proactive answer that restores soil capability, strengthens resilience and grants lengthy-time period health advantages without harming short-term crop boom, making it a key strategy for sustainable soil management (75).

Enhancing soil health via agro-ecosystem mimicry of natural ecosystems

Agroecosystems are human-controlled structures that differ from natural ecosystems in shape and functioning, making them more vulnerable to degradation and productivity decline. To enhance their long-term sustainability, concepts discovered in natural ecosystems may be tailored into agriculture in the form of smooth, farmer-friendly fashions. These fashions purpose to enhance soil health and productiveness on the equal time as very last economically viable, which is critical for adoption at the field level. Crop diversification via rotations or intercropping improves nutrient cycling, elevating SOC by means of 0.1–0.3 % consistent with year and improving microbial activity by way of 20–40 %, with productivity gains of 10–15 % from higher nutrient use and pest control. Residue retention with decreased tillage protects soil, improves shape and infiltration by 15–30 %, increases moisture in rainfed structures and stabilises yields with 5–10 % gains even as lowering fertiliser and irrigation needs (76). Intercropping and multi-story systems boost mild, water and nutrient performance, increasing land use through 20–30 % and nitrogen-use efficiency

with the aid of 10–25 %, at the same time as various roots fortify aggregation and reduce losses. Ecological intensification enhances soil organic, chemical and biological properties, constructing resilience towards drought, erosion and nutrient depletion. Economically, reduced reliance on fertiliser and insecticide cuts expenses by 15–30 %, elevating farm income. By mimicking natural ecosystems, those models assist healthier soils, sustained productivity and align well with conservation agriculture, natural farming and integrated systems, proving that ecological sustainability and profitability can go hand in hand (76).

Agroforestry and alternative agriculture for the management of soil health on marginal land

Effective management of degraded and marginal lands calls for species choice that balances ecological restoration with monetary returns. Agroforestry provides a realistic solution by means of integrating bushes, plants and now and again livestock to restore soil functions while producing income. Species choice relies upon local weather, soil constraints, water availability and desired outputs, along with fuelwood, fodder, wood, or soil development (77). In arid and semi-arid lands, drought-tolerant, deep-rooted trees like *Acacia senegal*, *Prosopis cineraria*, *Azadirachta indica* and *Dalbergia sissoo* stabilise soil and improve moisture retention. On reasonably degraded or culturable wastelands, leguminous trees along with *G. sepium*, *Sesbania sesban*, *Tephrosia* spp. and *L. leucocephala* fix nitrogen and decorate biological pastime. Grasses like *Cenchrus ciliaris*, *Panicum maximum* and *V. zizanioides* function as a floor cover, decreasing erosion, increasing SOC and supplying fodder (78). Management practices play an essential function in making sure the success of agroforestry structures. These encompass minimising soil disturbance, mulching with leaf litter, periodic pruning of bushes to lessen opposition and recycling biomass again into the soil to improve nutrient cycling. Proper spacing and temporal preparations are also critical to avoid excessive opposition to water and vitamins. Initial protection from grazing is vital for the duration of the status quo, while integrating farm animals later via managed grazing enables the use of fodder assets efficiently and returns vitamins to the soil via manure. Over time, agroforestry systems have been shown to enhance soil natural carbon by approximately 0.2–0.5 %, lessen erosion losses by means of 30–60 % and enhance microbial activity. These modifications regularly restore soil health, enhance resilience and enhance productivity, making agroforestry a sustainable approach for handling degraded and marginal lands (78).

Conclusion

Today, soil serves as a crucial resource for humans to satisfy their needs for temporary services from plants and animals that are retreating from agro-ecosystems, rather than only being a medium for plant development. Given the current state of land degradation, new strategies must be developed and put into practice in order to preserve soil health while maintaining or increasing agro-ecosystem productivity. The use of organic manures and other alternatives to complement and augment the chemical fertiliser-based strategy, together with the diversity of nutrient sources, are concepts that might greatly improve soil health. Given their potential to promote soil health, it makes sense to diversify production methods by implementing conservation agriculture and organic farming. In addition to improving resource usage efficiency, the closed system

of nutrient cycling made possible by an integrated farming system will be a self-sufficient alternative for managing soil health. To improve soil microbial diversity and reduce soil pollution brought on by the widespread use of agrochemicals (such as chemical fertilisers), it is necessary to pay attention to the biological health of the soil.

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Authors' contributions

BSSSN, SS, and SKS conceptualised the study and contributed to the overall design of the research on sustainable soil health management. SS drafted the manuscript and coordinated the integration of agronomic and technological aspects. MMR, SKY and KPCR contributed to data collection, agronomic analysis and interpretation of soil health parameters. KGR, MSK and ARR participated in reviewing literature related to novel agronomic approaches and assisted in manuscript preparation. BSK and AB contributed to technological interventions, including analysis of precision agriculture tools and digital applications. GKR, RNM and PG were involved in data validation, interpretation and critical revision of the manuscript. KV, JSB and KVR assisted in compiling results, formatting and technical editing. KSR and TR contributed to final proofreading, refinement and overall coordination of the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

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