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Soil Health and Its Improvement Through Novel Agronomic and Innovative Approaches

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Soil is an important natural resource providing water, nutrient, and mechanical support for plant growth. In agroecosystem, continuous manipulation of soil is going on due to addition of input, removal of nutrients, changing water balance, and microbial life. These processes affect soil properties (physical, chemical, and biological), and the deviation of these properties from the normal status is controlled by soil buffering capacity and soil resilience. If these changes are beyond the reach of soil resilience, then soil loses its original state, leading to soil degradation. At present, the extent of the degraded area in the world is 1,036 to 1,470 million ha. This urges the need for maintaining soil health rather than the mere addition of input for crop production. Soil health is an integrative property that reflects the capacity of soil to respond to agricultural intervention, so that it continues to support both agricultural production and the provision of other ecosystem services. Maintaining the physical, chemical, and biological properties of soil is needed to keep it healthy, and this is possible through the adoption of different agronomic approaches. The diversification of nutrient sources with emphasis on organic sources, adoption of principles of conservation agriculture, enhancement of soil microbial diversity, efficient resource recycling through the integrated farming system, and amendment addition for correcting soil reactions are potential options for improving soil health, and are discussed in this review. This article reviewed the concept of soil health and its development, issues related to soil health, and indicators of healthy soil. At the same time, the impact of the ill health of the soil on crop productivity and resource use efficiency reported in different parts of the world in recent years are also reviewed. The agro-techniques such as green and brown manuring in arable land and agroforestry on degraded and marginal land were followed on piece meal basis and for economic gain. The potential of these and several other options for maintaining soil need to be recognized, evaluated, and quantified for their wider application on the front of soil health management avenues. The use of crop residue, agro-industrial waste, and untreated mineral or industrial waste (basic slag, phosphogypsum, etc.) as soil amendments has a huge potential in maintaining healthy soil along with serving as sources of crop nutrition. The review emphasizes the evaluation and quantification of present-day followed agro-techniques for their contribution to soil health improvement across agro-climatic regions and for wider implications. Furthermore, emphasis is given to innovative approaches for soil health management rather than mere application of manures and fertilizers for crop nutrition.

Keywords: integrated farming system, novel agronomic approaches, soil degradation, soil health, conservation tillage, soil microbial diversity

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INTRODUCTION TO SOIL HEALTH

The soil, supplier of water, nutrient, and mechanical support to crop plants, is explained as four-dimensional, unconsolidated, and dynamic in nature (Lal, 2016). The major components of the soil system consist of mineral matter, which acts as an inherent source of 14 essential mineral plant nutrients and organic matter, which acts as a storehouse (Elixir). Soil also supplies essential mineral plant nutrients along with carbon and pore space occupied by water and air supplying three basic non-mineral plant nutrients *viz*., carbon (C), oxygen (O), and hydrogen (H). In the ideal state, the proportions of these factors are 45% mineral matter and 5% organic matter; while the remaining 50% is occupied by pore space. This four-dimensional nature and distinct proportions of solid and pore space give soil distinct physical, chemical, and biological properties that change over time dimensions. Any significant variation in these factors beyond the range of crop tolerance limits makes soil unfit for crop cultivation and will be the most important reason for soil illness. The tolerance limit for plant growth is expressed as the different parameters that express the physical, chemical, and biological properties of the soils; while the soil with all properties in the acceptable range is considered healthy.

Soil health is defined by various authors in different ways because of the involvement of a large number of soil health indicators (Van Bruggen and Semenov, 2000; Nielsen and Winding, 2002; Brevik, 2009; Katyal et al., 2016; Haney et al., 2018; Wander et al., 2019) and their suitable combination for different land use systems. Definitions given by different authors and organization are shown in **Table 1**. The concept of soil health started with the use of the term "soil health" by Wallace (1910) in regard to the capacity of humus to provide a solution to almost all soil-related problems and the major historical development of the concept of soil health (Brivik, 2018) is shown in **Table 2**. As different soil properties are considered in explaining the concept of soil health, and act as indicators of soil health, it can also be defined in terms of soil properties *viz*. soil physical health, soil chemical health, and soil biological health. The soil with the ability to meet plant and ecosystem requirements for water, aeration, and strength over time, and to resist and recover from processes that might diminish this ability is considered as physically healthy (McKenzie et al., 2011; Are, 2019). Soil biological health is the ability of soil to support large and diverse microbial communities, suppress pathogens, and support healthy crop development (Brackin et al., 2017); while chemically healthy soil has plant nutrients in optimum quantity, available form, and balanced proportions, and which are available to plants without the hindrance of other chemical compound and properties. Soil chemical health also considers the presence or absence of harmful soil agrochemicals and pollutants.

Considering the variety of chemical, physical, and biological properties of soils, there were attempts to categorize some soil properties as indicators of soil health (Magdoff, 2001; Brevik, 2009; Cardoso et al., 2013; Haney et al., 2018; Pawlas et al., 2019), which are mentioned in **Table 3**. Along with soil health indicators, Magdoff (2001) listed the characteristics of healthy soil (**Table 4**). The importance of soil health in sustaining the agricultural ecosystem is well-recognized (Wienhold et al., 2008; Jat et al., 2015; NAAS, 2018; Jian et al., 2020; Tahat et al., 2020), and considering the varied levels of sensitivity of soil health indicators (**Table 3**), it is imperative to discuss the different issues and concerns of soil health.

TABLE 1 | Definitions of soil health given by different authors.

Sl. No.	Definition	References
1.	The ecological equilibrium and the functionality of a soil and its capacity to maintain a well-balanced ecosystem with high biodiversity (above and below surface) and productivity	Cardoso et al., 2013
2.	An integrative property that reflects the capacity of soil to respond to agricultural intervention, so that it continues to support both the agricultural production and the provision of other ecosystem services.	Kibblewhite et al., 2008
3.	The capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality and promote plant and animal health.	Doran and Zeiss, 2000; FAO, 2008
4.	The soil health refers to self-regulation, stability, resilience and lack of stress symptoms in a soil as an ecosystem.	Katyal et al., 2016
5.	The state of the soil being in sound physical, chemical and biological condition, having the capability to sustain the growth and development of land plants	Idowu et al., 2019
6.	A soil which acts as a dynamic living system that delivers multiple ecosystem services, such as sustaining water quality and plant productivity, controlling soil nutrient recycling, decomposition process and removing greenhouse gases from the atmosphere is considered as healthy soil	Tahat et al., 2020
7.	Soil health also referred as soil quality and is defined as the continued capacity of soil to function as vital living ecosystem that sustain plants, animals and humans.	Natural resource conservation service, USDA
8.	Soil health is the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality and support human health and habitation.	Soil Science Society of America

ISSUES RELATED WITH SOIL HEALTH

Factors that cause deviation of healthy soil are issues related with soil health, and the level of impact of these factors on soil health decides their order of significance and make them a concern. Studies on these issues are important because of the following reasons:

- The health of soil has a direct influence on the sustainability of agro-ecosystems, as soil is a feeding substratum for all types of vegetation.
- Healthy soil will be more resilient to extreme weather phenomenon (drought, flood, etc.) and frequency of these

TABLE 2 | Historical development of the concept of soil health.

Sl. No.	Scientist / organization	Statement / contributions	References
1.	H. A. Wallace (1910)	Use the term soil health with respect to capacity of humus obtained from manure to do many things and its seems to be a cure all in maintaining soil health	Wallace, 1910
2.	Stafford (1931)	Mentioned the significance of soil biology in the concept of soil health. He mentioned that, wider spacing and planting of only one crop tree act as soil improvers	Stafford, 1931
3.	USDA (1936)	The USDA's Agricultural Adjustment Administration published "Soil Health and National Wealth" in 1936. The concept of soil health is related with soil fertility along with role of microorganisms in enhancing the soil nutrient improvement and plant growth.	Brivik, 2018
4.	Wrench (1939)	He connect the soil health with human health and state that "it seems that human health is a consecutive process starting from the dieting and nutrition of the soil itself"	Wrench, 1939
5.	Bennett (1943)	Emphasis the elimination of wasteful land use processes and adoption of different soil conservation practices. He was among those initial workers who highlight the soil health concept and its relation with human health	Bennett, 1943
6.	Qureshi and Njihia (1984)	Initiation of benchmark trials to monitor soil health was one of the important resolutions adopted for research in future	Qureshi and Njihia, 1984
7.	Scofield (1986)	Connect the concept of organic farming given by Balfour (1943), Howard (1943) and Rodale (1945) with soil health and soil erosion	Scofield, 1986
8.	Swaminathan (1987)	State the significance of agroforestry in maintaining and improving soil health in long run	Swaminathan, 1987
9.	Haberern (1992)	Recognized the need and significance of acknowledging the problems of soil and soil health index	Haberern, 1992
10.	Romig et al. (1995)	Mentioned that, concern of soil quality is not limited to agricultural scientist, natural resource managers and policy makers; Farmers also have interest in soil quality (The soil quality is used synonymously to soil health)	Romig et al., 1995
11.	Halvorson et al. (1996)	Development of method to access and monitor soil quality by integration of multiple soil parameters	Halvorson et al., 1996
12.	Van Bruggen and Semenov (2000)	Suggested the systemic ecological approach to the search for indicators for soil health with major emphasis on soil biological characteristics	Van Bruggen and Semenov, 2000
13.	2013	Soil health institute was formed by "Samuel Roberts Noble Foundation and the Farm Foundation"	-
14.	2014	Soil Health Division formed by USDA national Resource Conservation Center in 2014	-
15.	-	Connection the soil health with human health	Brevik and Burgess, 2013; Brevik and Sauer, 2015; Brevik et al., 2017
16.	2017	Concept of soil security	Field, 2017

Brivik (2018).

phenomenons is expected to increase on the front of climate change (Mirzabaev et al., 2019; Olsson et al., 2019).

- A healthy soil should provide more ecosystem services such as biogeochemical cycling of nutrients, enhanced microbial population, and diversity (Costanza et al., 1997; Baveye et al., 2016).
- Maintaining soil health contributes to the sustainable development goals of the United Nations, such as alleviating poverty, reducing hunger, improving health, and promoting economic development (Lal, 2016).
- Maintaining soil health is now almost important for enhancing crop productivity because of the occurrence of multi-nutritional deficiency in soil (Rattan et al., 2009), increased soil degradation (Bhattacharyya et al., 2015), and accumulation of harmful pesticide residues in soil that adversely affect soil microorganisms (Meena et al., 2020).
- Maintaining soil health also contributes to carbon sequestration, as soil organic carbon is one of the most important criteria for soil health evaluation (Lal, 2016).
- Intensification of agriculture with imbalance in the use of artificial resources and less attention on the potential of natural resources adversely affects soil health.

Stakeholders, researchers, and policy planners have shown an increased attention for soil health management as proved by an increased rate of the adoption of conservation agriculture (Kassam et al., 2019), emphasis on organic farming, promotion of diversification in agriculture, development and adoption of

TABLE 3 | Soil health indicators and their measurements.

Soil health indicator	Unit of measurement	Ideal values for health soil indicators (agricultural soil)	Method of measurements and reference
Soil physical indicators			
Texture	12 classes based on the relative proportion of sand, silt and clay	Loam texture with 7–27% clay, 28–50% silt and 23–52% sand is considered as ideal for most of the crops	Bouyoucos hydrometer method andInternational pipette method; Bouyoucos, 1962; Gupta, 1998b
Bulk density	Gram cm^{-3} or Mg m^{-3}	1.33-1.35 g cm^{-3}	Direct and indirect methods; Casanova et al., 2016; Al-shammary et al., 2018
Penetration resistance	MegaPascal (MPa); N m^{-2} (cone index *N* cm^{-2})	–	Cone penitrometer; Gupta, 1998c; Herrick and Jones, 2002
Aggregate stability	Mean weight diameter (mm); Geometric mean diameter (mm)	–	Wet sieving and dry sieving method; Yoder, 1936; Kemper, 1965; Chaudhary and Kar, 1998; Das and Chong, 1998
Water holding capacity	mm m^{-1} depth of soil	Crop specific	Pressure plate and membrane apparatus; Richards and Weaver, 1943
Infiltration rate	mm $hour^{-1}$	–	Ring infiltrometer; Johnson, 1963; Sur and Gupta, 1998
Depth of hardpan	Indicated as depth from the surface at which hardpan observe	Based on the effective root zone depth and characteristics of plant	Determined by compaction of soil at different layers; Gerard et al., 1964; Batey, 2009
Depth ofwater table	Depth from the surface in meters	–	Paizometer and open well; Bouma et al., 1980; Sekhar et al., 2018
Porosity	Percentage (%)	50% of the total soil volume	Mercury intrusion porosimetry; Image analysis and soil micromorphology; Gupta, 1998a; Pagliai and Painuli, 1998; Rao and Jo, 1998
Erosive potential	Mg ha^{-1} soil $lossyear^{-1}$	$\leq$ 11 Mg ha^{-1} soil loss/year (permissible limit)	Universal soil loss equation; Wishmeier and Smith, 1960; Wischmeier and Smith, 1978
Soil structure	Expressed as types (Platy, prismatic, blocky and spheroidal),class (Very fine, fine/thin, medium, coarse/thick and very course) and grade (structureless, weak, moderate and strong)	Speroidal (granular and crumby)	–
Soil crust	Qualitative property indicated by either types of crust or by surface hardness measured by cone penitrometer	Soil should be crust free as all crust has adverse from cultivation point of view except soil biological crust in some cases	Optical and scanning electron microscopy; Williams et al., 2018
pH	In scale of 1–14	Neutral (6.7–7.3) pH for most of the crops and soil functioning is considered as ideal	Soil in water or 0.1 M KCl or 0.01 M $CaCl_2$ solution in ratio of 1:2.5–10; Prasad et al., 2006
Electrical conductivity	dS m^{-1}	–	Saturation soil extract or soil-water suspension (1:2 or 1:2.5; Rao and Reddy, 2013
Organic matter	%	–	Walkley and Black, 1934
Total organic carbon	% or g kg^{-1}	Ranges of values: Low < 0.5%, Medium 0.5–0.75% and High > 0.75%	Walkley and Black, 1934; Tandon, 2013
Total soil nitrogen	mg kg^{-1} soil or kg ha^{-1}	–	Kjeldahl method; Bremner, 1960; Nelson and Sommers, 1980
Cation exchange capacity	Milliequivalent 100^{-1} gram soil or Cmol(p+) kg^{-1}soil	–	Ammonium acetate extraction method; Barium chloride ($BaCl_2$) compulsive exchange method; Chapman, 1965; Gillman and Sumpter, 1986
Major nutrients			
Available soil nitrogen (Alkaline permanganate extractable)	mg kg^{-1} soil or kg ha^{-1}	Low <280 kg ha^{-1}, Medium 280–560 kg ha^{-1} and High > 560 $kgha^{-1}$	Alkaline permanganate method; Subbiah and Asija, 1956
Available soil phosphorus ($NaHCO_3$ extractable)	mg kg^{-1} soil or kg ha^{-1}	Low < 5 mg kg^{-1}, Medium 5–10 mg kg^{-1} and High > 10 mg kg^{-1}	Olsen et al., 1954; Olsen and Sommers, 1982

(Continued)

TABLE 3 | Continued

Soil health indicator	Unit of measurement	Ideal values for health soil indicators (agricultural soil)	Method of measurements and reference
Available soil potassium (Ammonium acetate extractable)	mg kg^{-1} soil or kg ha^{-1}	Low < 108 kg ha^{-1}, Medium 108–280 kg ha^{-1} and High > 280 kg ha^{-1}	Flame photometery method; Prasad et al., 2006
Available soil calcium	Milliequivalent liter^{-1} or milliequivalent 100^{-1} gram soil	–	Titration with EDTA; Hesse, 1971
Magnesium			
Sulfur	kg ha^{-1}	–	Turbidimetric method; Williams and Steinberg, 1959
Minor nutrients#			
Iron (Fe)	mg kg^{-1}	4.5 mg kg^{-1} soil	DTPA extraction and determination with atomic absorption spectrophotometer (AAS; Lindsay and Norvell, 1978
Manganese (Mn)		2.0 mg kg^{-1} soil	
Zinc (Zn)		0.6 mg kg^{-1} soil	
Copper (Cu)		0.2 mg kg^{-1} soil	
Boron (B)	mg kg^{-1}	0.5 mg kg^{-1} soil	Hot-water soluble boron; Singh et al., 1999
Chlorine (Cl)	–	–	–
Molybdenum (Mo)	mg kg^{-1}	0.2 μg g^{-1}soil	Grigg's reagent (Ammonium oxalate at pH 3.3; Gupta, 2013)
Nickel (Ni)	–	–	–
Microbial biomass carbon	(μg microbial biomass carbon g^{-1} soil)	–	Fumigation method; Nunan et al., 1998
Earthworm populations	Numbers		Electro-shocking methodology; Weyers et al., 2008
Nematode populations	Numbers g^{-1} soil or Numbers root tip^{-1}	–	Spectrophotometric method; Patel and McFadden (1976)
Arthropod populations	Population density (numbers gram^{-1} of soil)	–	Sticky boards, pitfall traps or sweet nets methods of sampling; Norment, 1987
Mycorrhizal fungi	–	–	Magnified intersections methods; McGonigle et al., 1990
Nitrogen fixation of microorganisms	n mole ethylene g^{-1} h^{-1}	–	Acetylene reductase activity; Stewart et al., 1967
Soil chlorophyll	(mg g^{-1})	–	Extraction using organic solvent; Nayak et al., 2004
Dehydrogenase activity	(μg TPF g^{-1} soil day^{-1})	–	Triphenyl tetrazolium chloride test; Casida et al., 1964
Alkaline phosphatase activity	(μg PNP g^{-1} of soil hr^{-1})	–	*p*-nitrophenyl phosphate method; Tabatabai and Bremner, 1969
Urease enzyme	–	–	Soil incubation in tri(hydroxymethyl) aminomethane buffer; Tabatabai and Bremner, 1972
Soil respiration rate (Soil CO_2 efflux)	μ mol m^{-2} s^{-1}	–	Closed or open dynamic system; Davidson et al., 2002

Minor nutrients#: critical limits for soil deficiency are given.

land use classification (USDA, 1961; Grose, 1999), and adoption of farming system-based approach rather than using cropping system alone. Policies/schemes such as soil health card schemes also address one or more soil health-related issues (Wienhold et al., 2008; Anonymous, 2011; Islam et al., 2017; Reddy, 2017). Terms mainly used to describe degraded soil health are land degradation, soil degradation, soil desertification, and soil pollution. Land degradation is the loss of actual or potential productivity or utility as a result of natural or anthropogenic factors. It is a decline in land quality or a reduction in land productivity (Eswaran et al., 2001); while IPCC (Olsson et al., 2019) define land degradation as a native trend in land condition, caused by direct or indirect human-induced processes such as anthropogenic climate change, expressed as long-term reduction or loss in at least one of the following: biological productivity, ecological integrity, or value to humans. Soil degradation is considered as a subset of land degradation (Olsson et al., 2019), which directly affects soil and is defined as a decline in the

TABLE 4 | Characteristics of healthy soil.

Sl. No.	Attributes	Description
1.	Important function of healthy soil	Carbon transformations, nutrient cycles, soil structure maintenance, regulation of pests and diseases
2.	Sufficient supply of nutrients although	There needs to be sufficient nutrient supply for plant growth, at the end of the season there should not be too much nitrogen and phosphorous left in highly soluble forms or enriching the soil surface. Leaching and runoff of nutrients are most likely to occur after crops are harvested and before the next crops are well-established
3.	Good soil tilth	Soil with good tilth is spongier and less compact and allows roots to more fully develop than a soil with poor tilth. A soil that has a favorable and stable soil structure also promotes water infiltration and storage for later plant use
4.	Sufficient depth	Soils with sufficient depth to a layer that can restrict drainage and (or) root development promote full root system development
5.	Good internal drainage	Timely field operations can occur when soils dry quickly. Also, oxygen must be able to reach the root zone to promote optimal root health and that is best with good drainage
6.	Low populations of parasites	Crop yields are higher when plants are not harmed by parasitic bacteria, fungi, or nematodes etc.
7.	High populations of plant-growthpromoting organisms	Organisms, such as earthworms and many bacteria, fungi, and actinomyceteshelp in cycling of nutrients and make them available to plants. Soil organisms also produce plantgrowth-promoting substances
8.	Low weed pressure	Having few weeds is important so there is little competition with the crop for nutrients, water and light
9.	No chemicals that harm plants	Harmful chemicals can occur naturally, such as soluble aluminum in acidic soils or excess salts in arid regions. Potentially harmful chemicals may be introduced by human activity, such as fuel-oil spills, or the application of sewage sludge that has high concentrations of toxic elements
10.	Resistance to being degraded	Soils with good tilth and internal drainage and that have low populations of plant parasites can better resist the negative effects of compaction or periods of wetweather
11.	Resilience	Healthy soils are able to recover quickly after unfavorable changes, such as compaction

Magdoff (2001).

productivity of soil through adverse changes in nutrient status, soil organic matter, structural attributes, and concentrations of electrolytes and toxic chemicals (Aulakh and Sidhu, 2015). The other term, soil desertification, is mainly related to the physical degradation of soil and is defined as land degradation in arid, semi-arid, and dry sub-humid areas, collectively known as drylands, resulting from many factors, such as human activities and climatic variations (Mirzabaev et al., 2019). The term soil pollution was defined as the build-up of persistence toxic compounds, chemicals, salts, radioactive materials, or disease-causing agents in soils, which have an adverse effect on plant growth and animal health (Okrent, 1999). In this section, issues of soil degradation are discussed separately in three headings *viz*. physical, chemical, and biological degradation of soil. This will help in addressing the wide variation in factors that needs to be taken into consideration while discussing the issues of soil degradation.

Soil Physical Degradation

Major processes that cause physical degradation in soil include water erosion, wind erosion, wave erosion, coastal erosion, soil crusting, compaction, and hardening (Saha, 2003; Karlen and Rice, 2015). At the same time, agricultural practices that cause soil physical degradation include increased tillage intensity, inappropriate timing of tillage, aerobic-anaerobic cycles of soil moisture status in intensive cereal-based cropping systems (rice-wheat cropping system; Chauhan et al., 2012), lower addition of bulky organic manures, and removal of all dry matter produced, making soil devoid of vegetation. Soil physical degradation is mainly caused by either loss of soil from the area or modification of soil physical properties without any accountable loss in soil from the area.

Loss of Soil From the Area

Among the above-mentioned processes, soil erosion is the most prominent cause of soil physical degradation. At a global level, the estimated area affected by land degradation is 19.65 million km^2 (Obalum et al., 2017); while in India, the estimated area affected by soil erosion is 31.5 to 166.1 million ha (m ha) (Bhattacharyya et al., 2015) with total soil losses of 5,334 million tons $year^{-1}$ (16.35 t $ha^{-1} year^{-1}$) (Dhruvanarayana and Babu, 1983; Aulakh and Sidhu, 2015). Bhattacharyya et al. (2015) reported that a 94-mha area is affected by water erosion and 9 mha by wind erosion; while Lal (2001) reported that the area affected by water erosion and wind erosion was 32.8 and 10.8 m ha, respectively. In the process of soil erosion, detachment and

TABLE 5 | Soil erosion losses in different parts of India.

Sl. No.	Area	Soil erosion loses
1.	Dense forest, snow-clad cold deserts and the arid region of western Rajasthan	5 Mg $ha^{-1} yr^{-1}$
2.	Ravines along the banks of the Yamuna, Chambal, Mahi, Tapti and Krishna Rivers and in the shifting cultivation regions of Odisha and the north eastern states	Exceeding 40 $Mgha^{-1} yr^{-1}$
3.	Western Ghats coastal regions	20–30 Mg $ha^{-1} yr^{-1}$
4.	Erosion rates in the black soil region (vertisols) of the country, occupying a 64 million ha area in Karnataka, Andhra Pradesh, Madhya Pradesh and Maharashtra	20 Mg $ha^{-1} yr^{-1}$
5.	Red soils of Chhotnagpur plateau	10–15 Mg $ha^{-1} yr^{-1}$
6.	The north western hills of Jammu and Kashmir, Himachal Pradesh and Uttar Pradesh and the north eastern hills of Bengal and the north eastern states	More than 20 Mg $ha^{-1} yr^{-1}$
7.	Foothills of the Himalayas and the Doon Valley	20 Mg $ha^{-1} yr^{-1}$
8.	• Alluvial Indo-Gangetic Plains of Punjab, Haryana, Uttar Pradesh, Bihar and West Bengal • Salt-affected saline and sodic soils of these plains	• 5–10 Mg $ha^{-1} yr^{-1}$ • 5 Mg $ha^{-1} yr^{-1}$
9.	Shiwalik hills	More than 80 Mg $ha^{-1} yr^{-1}$

Singh et al. (1992).

transportation of soil particles happen from one place to another. Dhruvanarayana and Babu (1983) reported that 29% of the total displaced soil is lost permanently to the sea. Agents causing soil erosion are water and wind; the erosion caused by the combined action of water and wind that prominently occurs along canals and river banks is called wave erosion. Factors that decide the rate of water erosion are rainfall characteristics (intensity, distribution, and frequency), soil erodibility, steepness and length of the slope, crop cultivation practices, special practices for erosion control, and the erosivity of an agent (water) that causes erosion. The relative significance of these factors are varied over time, and space dimension and soil erosion were calculated from these factors using the Universal Soil Loss Equation (USLE) given by Wishmeier and Smith (1960), Wischmeier and Smith (1978). Factors affecting wind erosion are soil cloddiness, surface cover, surface roughness, soil textural class, local wind factor, wind width factor, wind direction, and wind barrier, while the functional relationship of these factors and the calculation of soil losses by wind erosion were given by Woodruff and Siddoway (1965). Singh et al. (1992) made an attempt to locate e iso-erosion lines on the map of India and quantify the rate of soil erosion in different areas (**Table 5**). The loss of soil due to erosion, according to them, ranges from 5 to 80 Mg ha^{-1} $year^{-1}$.

Modification of Soil Physical Properties

Crusting and compaction: Soil crusting is a surface phenomenon in which a hard thin layer of soil is formed on the surface of the soil. Valentin and Brasson (1997) defined soil crusting as the forming processes and the consequences of a thin layer at the soil surface with reduced porosity and high penetration resistance. In the formation of a soil crust, soil aggregates get broken down and the soil becomes more compact with less porosity (Manyevere et al., 2015). The properties of the soil are modified due to crust formation leading to (a) initiation or increase rate of erosion; (b) adverse effect on plant germination and crop growth and; (c) modification of water entry and movement. Another term used to describe soil crusting is surface sealing, and Morin (1993) defined surface sealing as the orientation and packing of dispersed soil particles that are disintegrated from soil aggregates because of the impact of rain drops. The types of crusts are structural, depositional, erosion, chemical, and biological (Valentin and Brasson, 1992; Morin, 1993; Pagliai and Stoops, 2010; Williams et al., 2018), and are defined as follows (Valentin and Brasson, 1992):

- Structural crusts: These are crusts that formed because of the *in-situ* arrangement of soil particles/aggregates without any lateral movement, and based on their morphology and formation process they are named as slaking crust, infiltration crust, coalescing crust, and sieving crust. The USDA natural resource conservation service defined soil structural crusts as relatively thin, dense, somewhat continuous layers of non-aggregated soil particles on the surface of tilled and exposed soils.
- Depositional crusts: In this type of crust, an external material is involved, and they are formed when the external material is carried by the flow of water settled after infiltration and evaporation of water.
- Erosion crusts: Erosion crusts consist of only a rigid, thin, and smooth surface layer enriched in fine particles (Valentin and Brasson, 1992).
- Chemical crusts: These are a type of crust formed because of the precipitation of chemicals or salts with surface sealing/hardening properties.
- Biological crusts: Formed because of colonization of different microorganisms forming community all around soil particles/aggregates. The distinctive characteristic of this type of crust is that it protects soil from erosion, and it contributes to soil organic carbon and nutrient accumulation (Belnap, 2005).

Mechanisms of crust formation

- Mechanical destruction of soil surface aggregates by raindrop impact (Le Bissonnais, 1996).
- Leaching of fine particles and their subsequent deposition in underlying pores.
- Compaction of soil surface to form a thin film that restricts both further entry of water and movements of fine particles in soil pores.
- Chemical dispersion of clay particles.
- Soil degradation due to intensive land use.

The formation of soil crust contributes to soil erosion and, ultimately, to soil degradation in one of the following ways:

- decreased hydraulic conductivity and infiltration rate (Nciizah and Wakindiki, 2015);
- loosening of soil aggregates, decrease in aggregate stability and, ultimately, disturbance in soil structure;
- increases the rate of runoff;
- and the deposition of eroded materials, which causes surface sealing.

Major soil and climatic conditions that promote soil crust formation:

- medium-textured soil;
- predominance of smectite, illite, and micaceous minerals;
- high exchangeable sodium percentage and low organic matter;
- in arid and semi-arid regions but also commonly occur in cultivated soils in other climates (Williams et al., 2018);
- and water content during a rainfall event.

Soil compaction: It is the state of land in which soil porosity decrease is accompanied by an increase in bulk density. Major reasons for soil compaction include: continuous tillage at same soil depths, higher traffic, continuous use of heavy machinery, tillage practices at improper moisture in the soil, and decreased addition of organic amendments. Soil compaction affects soil health similarly as that of soil crust in surface layer; while below soil surface layers, decreased porosity, increased bulk density, reduction in downward and lateral movements of water are the other important effects of soil compaction that negatively affect soil health parameters.

Soil desertification: Soil desertification is another type of land degradation whose impact not only limits soil health assessment but is also important from the point of view of climate change, food security, and economics (Anonymous, 2018b; Mirzabaev et al., 2019; Wijitkosum, 2020). The organization of a conference on desertification by the United Nations in 1977, the constitution of the United Nations Convention to Combat Desertification (UNCCD) in 1994, and soil desertification place in sustainable development goal number 15 also highlight the severity of the problem. The term desertification was used for the first time in a broader sense by Aubreville in 1949 (after Luvauden in 1927). It is defined as the type of land degradation in arid, semi-arid, or dry sub-humid areas caused by human activities and climatic variation; while Sterk and Stoorvogel (2020) considered it as land degradation in dry land areas. The conference on desertification by the United Nations described the phenomenon of desertification as "the diminution or destruction of the biological potential of the land, which can lead ultimately to desert-like conditions. It is an aspect of the widespread deterioration of ecosystems and has diminished or destroyed the biological potential (plant and animal production), for multiple use purposes at a time when increased productivity is needed to support growing populations in quest of development." The most recent estimate (Le et al., 2014) cited in Sterk and Stoorvogel (2020) indicated that, a 1,470-million-ha area, which is 29% of the total dry land, is affected by one or the other types of desertification; while Sterk and Stoorvogel (2020) had an opinion that a 1,036-million-ha area, which is 20.5% of total dry land, is affected by some form of soil degradation. In India, an 82.34-million-ha area (Anonymous, 2018b) is affected by desertification and includes all areas affected by one or the other types of land degradation. The extent of desertification is mainly judged based on the world map of the status of human-induced soil degradation, which was developed by the Global Assessment of Soil Degradation project (GLASOD) and based on expert knowledge of soil degradation processes and their spread in a large number of countries. According to a United Nations environmental program (Middleton and Thomas, 1997), desertification is the outcome of the following activities:

- climatic factors (temperature, rainfall, etc.),
- overgrazing,
- deforestation,
- agricultural activities,
- overexploitation of vegetation for domestic use,
- and bio-industrial activities.

Desertification contributes to the degradation of soil health through the following:

- rapid loss of vegetative cover on the soil surface and decrease in soil organic carbon;
- facilitation of the movement of soil/sand from one place to another, leading to expansion of desert;
- increased susceptibility of soil to wind and water erosion;
- adverse effect on the microbial population and diversity in the soil;
- and variation in soil surface relief and topography due to physical movement of soil.

Waterlogging: It is the state of soil moisture at which soil is saturated with water (all soil pores filled with water) and also used to indicate raising groundwater to the surface level (Awad and El Fakharany, 2020). In India, waterlogging is one of the important reasons for soil degradation, and the area affected by water logging is 11.6 million ha (Roy Chowdhury et al., 2018). The type may be surface waterlogging in which excess water is seen above the soil surface, or a subsurface type in which excess water remains below the soil surface. Soil characteristics, climate (rainfall), and plant cover have a profound influence on waterlogging. The areas and conditions in which waterlogging occurs are listed as follows:

- areas with heavy rainfall (the intensity of rainfall plays a major role);
- over irrigation mainly found in canal command areas in India;
- areas along river banks because of expansion of agricultural land up to riverbanks (mainly during flood situation);
- low elevated land where the collection of water causes waterlogging;
- areas around water reservoirs because of seepage of water;
- low infiltration rate and hardpan formation, and the presence of chemical salts, such as sodium and its compound aggravate the problem of waterlogging.

Water logging affects soil health adversely in one of the following ways:

- disturbing soil physical health through reduced aeration, structural stability, and lowering down of soil temperature;
- reducing soil oxygen level, anaerobically decomposing soil organic matter, and accumulating toxic gases and other products of decomposition;
- Change in soil reaction along with losses in soil nutrients through leaching and overland flow.
- changing soil microbial population from aerobic to anaerobic or facultative aerobic, which leads to adverse effects on several microbial processes and biogeochemical cycling of nutrients;
- and unfavorably affecting soil tillage properties and making soil unsuitable for cultivation of most crops.

Soil Chemical Degradation

Soil chemical health gets more attention from both researchers and stakeholders because of its most direct and significant influence on agricultural productivity, growing need for external addition of amendments and nutrient sources, and the profound influence of soil chemical properties on modification of soil biological and physical health. The chemical degradation of soil is discussed under the following subsections:

- Reduction in soil carbon;
- Changes in soil reaction (acidification and sodification);
- Modification of soil mineral nutrient status (nutrient imbalance, multi-nutrient deficiency);
- Accumulation of toxic compound (agrochemicals);
- and Soil pollution.

Reduction in Soil Organic Matter

Soil is an important carbon pool at the global level, with 1,895–2,530 Pg carbon, which is two times as that of carbon present in the atmosphere and three times as that of biotic carbon pool. Out of total carbon in soil, 695–930 Pg is inorganic and 1,200–1,600 Pg is organic in nature (Sahoo et al., 2019). Among these two fractions, organic carbon is more important from a soil health point of view, and studies on factors that have a significant impact on soil organic carbon are also important considering the significant decrease in soil organic carbon in Indian soil (Reddy, 2017) and in world agricultural production systems (Song et al., 2005; Grace et al., 2006; Gardi et al., 2016; Wiesmeier et al., 2016; Blecourt et al., 2019). At the same time, as soil organic carbon serves as a source and storehouse of plant nutrients, it has a great role in crop production improvement along with its significance in soil health. The functions of soil organic carbon in soil health, crop productivity, and ecosystem services are given in **Table 6**.

Factors affecting soil organic carbon status: Wide variations in land use changes and crop husbandry across agricultural production systems, and sensitivity of soil organic carbon to these changes, are responsible for significant variations in the organic carbon content of soil. The soil organic carbon content was affected in three different ways *viz*., decrease in soil organic carbon, improvement due to fertility addition, and changes due to crop cultivation. The decrease in soil organic carbon is mainly due to land use changes caused by tillage in arable crops and types of crops grown if considered at the agro-ecosystem level. The impact of tillage on soil organic carbon can be seen by comparing the plow-based conventional tillage system, which is widely followed all over the world, with conservation tillage, which is currently getting momentum because of its several positive impacts on soil, plant, and water (**Table 7**). In fact, the adverse effect of the conventional plow-based tillage system on soil health was one of the reasons for the origin of conservation tillage. The breaking of soil aggregates, exposure of soil organic carbon to different types of degradation and decomposition, complete removal of dry matter produced by crops, burning of crop residue, dependence on inorganic fertilizers, mono-cropping of few crops, and less addition of organic nutrient sources are factors that intensify the decrease in soil organic carbon; while three principles of conservation agriculture (Kassam et al., 2019) counteract these adverse effects of conventional tillage. At the same time, the availability of a large array of selective herbicides, availability of machinery for sowing and subsoil placement of fertilizer, and increased interest at research and development front in the modification of nutrient release patterns from crop residues through different ways (Singh et al., 2009b; Swarnalakshmi et al., 2013; Choudhary et al., 2016; Gangaiah and Prasad Babu, 2016) also promote conservation tillage-based agriculture.

In regard to the effect of fertility addition and crop cultivation on soil organic carbon, the results from several long-term experiments will be the proof for the same (Reddy et al., 2017). Improvement in soil organic carbon due to the addition of an optimum dose of chemical fertilizers and the combination of chemical fertilizers with organic sources, and a decrease in soil organic carbon over the years due to cultivation of crops (Mandal et al., 2007), are the major findings of long-term experiments in India. The variation in soil organic carbon in permanent agriculture has a different pattern compared with the growing of arable crops (Bernardi et al., 2007; Ganeshamurthy et al., 2020) because of variation in the frequency of land disturbances. Along with this, the variation in carbon sequestration potential of crops (Ghosh et al., 2006; Brar et al., 2015) is another important factor affecting soil organic carbon in cultivated areas.

In land use change, bringing the marginal land under cultivation has an adverse effect on soil organic carbon; while the utilization of degraded land for agro-forestry or energy plantation will successfully maintain or enhance soil organic carbon. Another land use change that significantly affects soil organic carbon content and most prominent innorth east India is shifting cultivation (Bhuyan, 2019). The clearing of natural vegetation and bringing the land under cultivation reduce soil organic carbon (Sharma et al., 2019).

Change in Soil Reactions (Acidification and Sodification)

The study on soil reactions for their effect on soil chemical health is also important because of the following reasons:

- Mineral nutrient availability is affected by soil reactions.
- Soil properties such as cation exchange capacity, base saturation, chelation of micronutrients, and anion exchange capacity, are responsible for the retention and movement of

TABLE 6 | Functions of soil organic carbon.

Plant	Soil			Ecosystem
	Improvement	**Maintenance**	**Reduce**	
Crop yield Improvement	Aggregate stability	Temperature	Bulk density	Increase in carbon sequestration
Quality improvement	Porosity	Soil consistence	Erodibility and erosion	Reduce greenhouse gas emission
Enhance resource use efficiency	Infiltration	Air circulation	Accumulation of toxic material	Prevent siltation of tanks and enhance their storage capacity and life
Profitability enhancement	Chelation of micronutrients	Optimum soil moisture	Reduce the leaching losses of nutrients	
Sustainability in production system	Cation exchange capacity and base saturation	pH	Soil crusting and compaction	
Reduce bioaccumulation of soil pollutants in the plant products	Water and nutrient retention capacity	Desirable soil structure (spheroidal –granular and crumby structure)		
Increase in duration of shifting cultivation area available for cultivation	Enhance the decomposition of soil pollutants			
	Microbial population and diversity			
	Biogeochemical cycling of nutrients			

TABLE 7 | Differences between conventional tillage and conservation tillage.

Sl. No.	Particulars	Conventional tillage	Conservation tillage
1.	Tillage system	High intensity; plow based tillage system	Minimum tillage or zero tillage
2.	Fallowing system	Ideal fallow land without any crop cover on soil surface	Growing of cover crops
3.	Residue management	Complete removal or burning of crop residue	Maintaining at least 30% soil surface covered with residue
4	Nutrient management	Chemical based nutrient management (intensive use of chemical fertilizers)	Integrated nutrient management with inclusion of organic sources and microbial inoculations
5.	Cropping system	Mono-cropping of crops or single cropping system	Diversified crops and crop rotation
6.	Soil health	Poor/ degraded	Healthy soil
7.	Energy requirement	Higher	Lower
8.	Sustainability	Lower	Higher
9.	Footprint on natural resources	Higher	Lower

nutrients in the soil. These properties change with a change in soil reaction.

- Soil physical properties such as aggregation and erodibility are also affected by a change in soil reactions. Mineral elements such as sodium have a significant impact on soil aggregation and their presence in soil is controlled, to a large extent, by soil reactions.
- The relative proportion of different forms of mineral nutrients present in soil and inter-convergence is affected by soil reactions.
- The biogeochemical cycling of nutrients and the role of microorganisms in it are also modified with changes in soil reactions.

A soil reaction near neutral pH is mostly suitable for the cultivation of crops and different properties of soil; while an abnormal change in soil reactions affects soil chemical health. Changes in soil reactions due to human-induced changes in soil, water, and plant are observed at a very slow rate because of buffering capacity of soil and predominance of soil mineral matters (occupying 45% of the total soil volume) in deciding soil reactions. Environmental factors that cause changes in soil reactions include:

- weather factors, mainly rainfall patterns and temperature (causes leaching and erosion of soil mineral and organic matter);
- climatic factors intensify weathering which creates changes in soil parent materials;
- and topographical factors, topography of surface, and presence or absence of vegetation on the soil surface.

Human-induced changes in soil pH are mainly caused by the application of amendments for improving soil properties (liming or gypsum application), fertility addition through organic and inorganic sources of nutrients, and changes in land use (Mishra et al., 2006b). The effect of both the natural- and human-induced factors on the pH of the soil is conditioned by time. Major reactions that make soil chemically unfit for agriculture include the following:

- **Acidification**: It is the process of decreasing soil pH to such an extent that the soil becomes unfit for cultivation, and it is caused by both natural- and human-induced processes. Major natural processes causing acidification include acid rain, application of acid-forming fertilizers, mineralization of organic matter, nutrient uptake by roots, root exudates, and nitrogen fixation by legumes (Goulding, 2016). Soil acidification adversely affects soil health by changing the modification of nutrient availability, soil microbial population, and toxicity to the roots of plants due to increased levels of one or more mineral element concentrations. The area under acidic soil conditions in India is 17.9 million ha (Anonymous, 2016); while in the world 3,950 mha of arable land is affected by soil acidity (Bian et al., 2013), indicating the severity of the problem.
- **Sodification**: This phenomenon is the opposite of soil acidification, because soil pH is increased by the predominance of carbonates and bicarbonates of sodium. The presence of sodium in soil significantly modifies the soil properties, thereby affecting soil health and productive potential. The major changes in soil due to sodification include dispersion of soil aggregates leading to poor soil physical condition, reduced hydraulic conductivity and infiltration rate, changes in nutrient availability, and toxicity of higher concentration of sodium to plant roots.

Modification of Soil Mineral Nutrient Status (Nutrient Imbalance, Multi-Nutrient Deficiency, and Nutrient Mining)

Among the major input additions in present-day agriculture, nutrient application plays an important role and is mainly due to the increased response of crops to nutrient application, crop and/or cropping system intensification in special and temporal dimensions to feed burgeoning population, and decrease in the level of soil nutrient status. The modification of soil nutritional status is mainly expressed as nutrient imbalance, multi-nutritional deficiency, and nutrient mining. The imbalance arises because of differential nutrient uptake and fertility addition, which does not match the plant uptake; while the present status of multi-nutritional deficiency was increased because of the addition of only primary nutrients (especially N and P) with complete dependence on soil nutrient reserves for other nutrients. Nutrient mining is another term used to indicate the negative balance between nutrient addition and nutrient removed by crops. At present, Indian soils are at negative balance of 8 to 10 million tons per year (NAAS, 2018); while Jones et al. (2013) and Henao and Baanante (2006) reported nutrient mining practices at the global level. The significance of soil mineral nutrient status with respect to soil health and overall agricultural productivity can be explained using the following points:

- increase in the number of nutrients showing deficiency in cultivated soil;
- extent of negative balance of nutrients in the soil;
- responsiveness of crops to the application of nutrients;
- possibility of reducing nutrient mining by utilizing crop by-products as a nutrient source and avoiding their ineffective use such as *in-situ* burning;
- share and role of organic material addition in meeting the nutrient need of agriculture;
- role of microbes in enhancing the nutritional status of soil;
- long-term effect of application of recommended rate of nutrients on soil nutrient status;
- short and long-term impact of nutrient mining on crop productivity and economics;
- effect of changing soil nutrient supplying capacity due to change in soil organic carbon in arable soils;
- effect of imbalance in the use of chemical fertilizers on soil nutritional status;
- lack of attention for soil and water conservation practices leading to loss of fertile top soil layer rich in plant nutrients;
- and soil fertility changes due to cultivation of crops on marginal and degraded land as well as intensive cereal-based crops/cropping systems with replacement of fertility restorer crops.

Accumulation of Toxic Compound (Agrochemicals)

This is the major source of toxic compound which get accumulated in soil thereby affect the soil health. The use of agrochemicals for plant protection and weed management leads to considerable increase in accumulation of toxic compound in soil. This can be seen from an increase in the use of agro-chemicals from 39,773 to 52,980 metric tons of technical grade material (Bhardwaj and Sharma, 2013; Indira Devi et al., 2017). Even with this significant increase in agrochemical consumption, per hectare consumption in India is 291 g ha^{-1}, which is far lesser than the consumption in developed countries (Indira Devi et al., 2017). The use of pesticides in Japan, China, and Mexico is 18.94, 10.45, and 7.87 kg ha^{-1}, respectively (Zhang, 2018). Along with that, excessive use of chemical salts to provide nutrition is the other source of toxic compounds. Some organic sources of crop nutrition, such as sewage and sludge and night soil, are also reported to contain a high amount of heavy metals (Walia and Goyal, 2010; Saha et al., 2018), causing adverse effects on soil health. The reason for the increasing contribution of agrochemicals to soil chemical degradation is their unregulated and uncontrolled use (Bhardwaj and Sharma, 2013) and lack of proper knowledge and awareness on the use of agrochemicals. The major adverse effects of using agrochemicals on soil health include: (i) adverse effect on the population dynamics of soil microflora and microfauna, (ii) affecting the rate of biogeochemical cycling of nutrients, and (iii) adverse effect on the growth of plants along with bioaccumulation of agrochemicals in plant and animals. Considering the role of agrochemicals in crop production and, overall, in agriculture, their complete elimination is difficult, but following regulations and recommendations in their use can be helpful in minimizing their build-up to an extent that they are causing adverse effects on soil health.

Soil Pollution

Soil pollution in cultivated fields is another emerging problem that is considered as a major outcome of modern agrochemical-based agriculture and lack of accounting of footprint of agricultural activities. Soil pollution is defined as a physical, chemical, biological, or radiological modification of the surface layer of the crust of the earth by the accumulation of a large quantity of natural materials or occurrence of new synthetic materials that disturb the composition of the soil, influence the natural balance of the ecological system, and disable the purification process (self-cleaning) of the soil (Backovic, 2008; Ashraf et al., 2014). The causes of soil pollution in agricultural land are:

- inappropriate use of chemical fertilizers especially phosphatic fertilizers, herbicides, and use of agrochemicals for insect-pest and diseases management;
- application of materials rich in pollutants and use of industrial waste;
- use of inferior plastic films;
- use of polluted water for irrigation;
- use of polluted area for agriculture or growing of crops along a city landfill;
- improper disposal of industrial wastes;
- seepage from landfills and percolation of pollutants along with infiltrating water;
- longer persistence of biochemical compounds in wastes and lack of soil flora and fauna for decomposition of agrochemicals;
- and neglecting the significance of soil pollution remediation measures.

These sources have varied effects on soil health and ultimately on agricultural productivity. The effects of soil pollutions are as follows:

- Soil properties such as porosity, base saturation, soil reaction, soil salinity, and nutrient toxicity are affected because of soil pollution (Backovic, 2008).
- Soil pollution caused by industrial waste or sewage-sludge may lead to the accumulation of heavy metals that may enter in the food web, leading to bioaccumulation of these heavy metals in animals or human beings, leading to several health hazards (Khan et al., 2015). The identification of adverse effects of such pollutants on human health sometimes becomes difficult, as they are seen after long exposure and continue across generation.
- The pollutants present in soil may escape and add to groundwater because of leaching or enter into above-ground water reservoirs, thereby causing pollution in these water bodies. This makes the water unsafe for use and also harms aquatic life (Khanna and Gupta, 2018).
- Pollutants that accumulate in soil up to the toxic level may affect the germination and growth of the next crop in succession.
- Soil pollution may adversely affect the population dynamics of soil microorganisms and thereby nutrient cycling.
- In extreme cases, they make soil unfit for normal crop cultivation.
- Pollutants such as heavy metals are non-degradable by any biological or physical means and therefore remain in soil over longer duration (Selvi et al., 2019).
- Heavy metal pollution is one of the hurdles of direct use of nutrient-containing minerals in agriculture and more especially in organic farming (Mortvedt, 1995).

Soil Biological Degradation

The biological properties of soil are the last to get attention. However, they started getting attention when their normal activities and functioning became affected significantly by modern agricultural practices. Soil biological degradation is defined as the impairment or elimination of one or more significant populations of microorganisms in the soil, often with resulting changes in biochemical processing within the associated ecosystem (Sims, 1990). At present, considering their significant role in different soil processes and functional activities, soil microbial properties are studied as rhizosphere dynamics (Kumar et al., 2013) and soil genomics (Singh et al., 2009a) level. Soil biological properties that can be used to judge the biologically degraded soil (Bedano et al., 2011; Lehman et al., 2015), as given by Mishra and Dhar (2004), are listed below:

- abnormality in microbial community diversity indicated by viable count (colony forming unit);
- reduction in either species richness or evenness of allocation of individuals among various species or both the above-mentioned characteristics;
- adversely affected major soil processes such as soil respiration, different enzyme activities, nutrient cycling, and degradation of organic compounds;
- symptoms of accumulation of toxic compounds in the soil due to their reduced rate of decomposition;
- and an increase in the population of undesirable microorganisms/pathogens causing diseases or serve as a vector for the transfer of different diseases.

The major difficulties in determining soil biological health and evaluating the indicators of soil biological health mentioned by Brackin et al. (2017) are as follows:

- complex relationships of soil microbial life with soil properties and crop plants;
- highly dynamic and sensitive to changes in soil management (such as tillage and amendment addition, etc.);
- difficulty in the identification and quantification of exact soil microbial life affecting soil health because of their very large diversity (Nielsen et al., 2016);
- and use in short-term evaluation because of their higher sensitivity to changes in soil conditions (Obalum et al., 2017).

Soil Ecosystem Services

There are several types of degradation processes acting side by side as discussed in previous sections (Soil Physical Degradation to Soil Ecosystem Services) due to continuous human interferences. All these processes lead to drastic changes in ecosystem services provided by the soil, as listed below:

- reduction in nutrient-supplying capacity of soil with a net negative nutrient balance;
- reduction in the rate of decomposition of soil pollutants due to biological degradation of soil;
- reduction in capacity to act as net carbon sinks because of continuous reduction in soil organic carbon content in most of the agricultural land;
- increasing and decreasing the population diversity of undesirable microbes (pathogen) and useful microbes in the soil;
- increase in areas under salt-affected soil conditions, thereby reducing their productivity potential;
- and reduction in productive potential and future carrying capacity of soil due to the above-mentioned five points.

At the same time, studies on soil ecosystem services are important because of the following points:

- increased level of the human footprint on natural resources;
- faster rate of degradation of natural resources;
- increasing concerns of climate change and its effect on soil ecosystem services;
- increase in the human and animal population, which increases the burden on limited natural resource;
- and economic and global model of development adopted by the world, with less consideration to ecological aspects.

EFFECT OF SOIL DEGRADATION ON PLANT GROWTH

Considering the level of degradation of soil as discussed in previous sections, the effect of land degradation on soil productivity needs to be quantified. In this section, attempts were made to review the effect of land degradation on plant growth using the study conducted by different researchers from different parts of the world.

Productivity and Profitability

The effect of several land degradation problems on crop productivity can be studied either by accounting for the losses in natural resources due to different processes at the global level, or from the reduced productive potential of degraded soil. In the European Union, Panagos et al. (2018) used microeconomics models and reported that 12 m ha of agricultural areas in the European Union have degraded soil. This led to economic losses in the agricultural sector to be close to €300 million and loss in GDP to be about €155 million. In Senegal, Sonneveld et al. (2016) reported that severe types of land degradation were associated with a decline in crop productivity. Pimentel and Burgess (2013) also reported a significant impact of soil erosion on food production. In the Canadian prairies, Cann et al. (1992) showed a compilation of the significant impacts of soil degradation on different crop yields. In India, Bhattacharyya et al. (2015) reported that the total cost of land degradation varies from US$1,037.94 to 6,191.81 million [1 US dollar ($) = 72.45 Indian rupee (₹)] per annum with the highest cost of land degradation due to soil erosion. This leads to a loss in crop production, which varies between US$93,305 and 4,982.71 million per annum. Zingore et al. (2015) reported different soil quality constraints for crop production in sub-Saharan Africa, and these problems, according to their significance in terms of area affected, are aluminum toxicity > low cation exchange capacity> soil erosion > high phosphorus fixation > vertic properties > salinity > sodicity. They reported that in sub-Saharan Africa the total crop production area affected by these soil constraints was 23 billion ha. These constraints are an indication of degraded soil, and significantly reduce the productivity of the soil. In Australia, Koch et al. (2015) reported the significance of soil security in achieving food security and provision of ecosystem services. Mythili and Goedecke (2016) used a total economic value approach for the calculation of the cost of land degradation and reported that the annual cost of land degradation in India in 2009 was US $5,152.46 million. This indicates that land degradation puts a significant economic footprint along with a footprint on natural resources.

Along with these impacts of soil degradation at a large landscape, the effect of different soil ill health on crop productivity and economics, as well as the response of crop grown in such soil to various amendments reported by different authors are summarized in **Table 8**. The significant contribution of soil degradation to the reduction in crop productivity can be judged from the accumulation of a large number of such studies (Frye et al., 1982; Lal and Moldenhauer, 1987; Pierce and Lal, 1994; Mantel and Van Engelen, 1997; Wiebe, 2003; Rickson et al., 2015). These different studies showed that soil physical and chemical degradation had a significant and negative impact on soil health. Along with it, the adverse effect of soil biological degradation was also reported (Song et al., 2017) showing a reduction in the germination of different grasses due to the formation of cyanobacteria-dominated crust.

Resource Use Efficiency

Soil salinity is one of the most important problems affecting soil health in irrigation command areas. In saline soil, the amount of water required is higher than the water required for raising crops on normal soil in order to maintain salt balance in root zone depth, and because of that, water productivity is lower in saline soil. In Iran, various options for improvement in

TABLE 8 | Effects of soil degradation on crop growth and productivity.

Sl. No.	Crop	Soil degradation related problem	Effect	Correction measure suggested	References
1.	Wheat	Salinity due to irrigation water	Reduction in grain and straw yield, harvest index and growth parameters of wheat with increase in electric conductivity of irrigation water from 0.7 to 12 dS m^{-1}	Use of *Azospirillum sp.* isolated from saline soil leads to significant improvement in grain yield of wheat over control.	Nia et al., 2012
2.	Rice bean	Soil acidity	Growth and yield of crops as well as economic parameters (gross and net return, B:C ratio, production efficiency and economic efficiency) was reduced due to soil acidity	Use of lime @ of 0.6 t ha^{-1} increase all growth and yield attributes with increase in 0.42 t ha^{-1} yield, 221.31 and 164.34 US $ gross and net returns ha^{-1}, respectively.	Kumar et al., 2014
3.	Rice	Acidity of soil (acid sulfate soil) and aluminum toxicity	Reduction in rice yield due to soil acidity and higher aluminum toxicity; lower availability of exchangeable cations (Ca, Mg and K)	Positive effect of addition of amendments such as magnesium limestone, sugarcane based organic fertilizers and fused magnesium phosphate	Shamshuddin et al., 2016
4.	Chickpea	Sensitivity of sodium salt (sodium chloride)	Vegetative and reproductive growth (number of flower buds and pods) is significantly affected due to the increase in sodium chloride concentration; podding stage of crop was found most susceptible	–	Samineni et al., 2011
5.	Rice	Acid soil and aluminum toxicity	Soil pH and soluble aluminum affect the growth parameters of rice	Application of wood biochar helps in reduction in soil pH and aluminum toxicity	Shetty and Prakesh, 2020
6.	Red gram and groundnut intercropping system	Soil salinity and poor soil fertility	Lower yield of both crops, shelling percent and oil content of groundnut as well as protein percent of red gram seed	Significant improvement in all the said parameters due to addition of paper mill sludge, farm yard manure and nutrient addition	Pattanayak et al., 2011
7.	French bean	Chemical degradation (nutrient deficiency) in acidic soil	Reduction in growth and yield attributes due to low soil fertility	Improvement in growth and yield attributes due to application of recommended rate of three primary nutrient along with boron	Kumar et al., 2016
8.	Chickpea	Soil salinity	Adverse effect of soil salinity on germination and growth	Improvement in germination early growth as studied with respect to following characteristics viz., germination percentage, germination rate, root length, shoot length, vigor index and total dry matter	Shaheenuzzamn, 2014
9.	Garden pea	Acidic soil	Adverse effect of soil acidity on growth of garden pea and soil properties	Positive effect of application of biochar of corn or *Lantana camera* (@ 6 to 18 t ha^{-1} on growth parameters of crop; Improvement in soil porosity, total nitrogen, available phosphorus and potassium content of soil after harvest of crop	Berihun et al., 2017
10.	Cereal based cropping system (Rice-wheat, Rice-wheat-green gram, Maize-wheat, maize-wheat-green gram)	In reclamation of sodic soil through conservation agriculture	Adverse effect of physical soil properties on crop growth as well as nutrient availability	Improvement in volumetric water content, reduction in water content, improvement in infiltration rate, increase in total nitrogen, available phosphorus and potassium in conservation agriculture based rice-wheat-green gram cropping system)	Jat et al., 2018
11.	Chickpea	Soil compaction	Adverse effect of higher bulk density on the root growth parameter such as root length density, root mass density, number of primary roots and number of nodes	-	Choudhary et al., 2015
12.	Rice-maize cropping system	Nutrient mining (potassium)	Reduction in exchangeable soil K after 1 year of rice-wheat cropping system by 5 mg ka^{-1} soil	Application of potassium increase rice yield by 1.8 t ha^{-1}	Timsina et al., 2013
13.	Grasses (*Eragrostis poaeoides* Beauv., *Artemisia capillaries* and *Stipa glareosa* P. Smirn.	Biological crust	The biological crust dominated by cyanobacteria significantly reduces the germination of all grasses.	The bare soil have highest germination of all grasses	Song et al., 2017

(Continued)

TABLE 8 | Continued

Sl. No.	Crop	Soil degradation related problem	Effect	Correction measure suggested	References
14.	Rice	Sodic soil	–	The pH, electric conductivity, exchangeable sodium concentration was significantly decreases; while organic carbon and alkaline $KMnO_4$ extractable carbon was significantly increased due to gypsum application	Singh et al., 2016
15.	Pea	Acidity of soil	–	Grain yield and dry matter production was improved due to application of lime @ 7.5 t ha^{-1} by 0.50–0.55 t ha^{-1} and 1.37–1.72 t ha^{-1}, respectively	Arshad and Gill, 1996
16.	Rice	Saline sodic soil	Negative effect of saline sodic soil on plant growth and yield	Application of gypsum @ 9.5 t ha^{-1} and irrigation at four 4 day interval showed significant improvement in the growth and yield attributes of rice along with significant improvement in grain and straw yield of rice	Hafez et al., 2015
17.	Wheat	Waterlogging	Waterlogging for 15 days imposed after 21 days of sowing reduce the yield of wheat in neutral soil (7.0 pH), saline soil (8.2 pH), sodic soil (9.0 pH) and sodic soil (9.4 pH).	-	Yaduvanshi et al., 2010

1 US$ = 72.45 Indian rupee (₹).

water productivity under saline soil conditions were reported by Heydari (2019). He showed that optimum border irrigation and basin irrigation had higher water productivity (1.36 and 1.04 kgm^{-3}) over the traditionally followed basin irrigation method. The salinity of irrigation water is also an important problem that leads to the build-up of soil salinity. Pressurized irrigation systems such as drip irrigation are reported to be most effective in improving water use efficiency and productivity; while the use of saline water for irrigation drip systems is a debatable issue due to root zone accumulation of salt and functioning of drip systems (clogging). Tingwu et al. (2003) showed that, use of saline water through drip irrigation on soil with $\leq$ 75% silt once every 2 days, at 60% of the Chinese pan evaporation had significantly higher yield and quality of watermelon over control even though water use efficiency in control (39.2 kg m^{-3}) was significantly higher than treatment with 60% of the Chinese pan evaporation (21.45 kg m^{-3}). They also reported that an increase in soil salinity build up averaged over soil profile in irrigation at 60% of the Chinese pan evaporation was very small over original soil salinity. Singh et al. (2018) reported that the application of irrigation water through a sprinkler or low energy water application each at 2 days interval with 4 cm depth at each irrigation significantly improved the water productivity and energy productivity over a surface method of irrigation with a similar level of rice grain yield in all irrigation systems. This finding again reports the successful use of a micro-irrigation system in problematic soil.

Nutrient use efficiency is another major challenge on the front of low nutrient use efficiency of major nutrients and reduction in the partial factor productivity of major nutrients due to multi-nutritional deficiency. Degradation of soil is one of the important reasons for the reduction in nutrient use efficiency and the need of higher fertilization. This can be clear from increasing the number of nutrients showing response to application (Rattan et al., 2009), the status of soil degradation (Bhattacharyya et al., 2015), and increase in the area showing the deficiency of secondary nutrients such as sulfur and micronutrients viz. Zn and Fe (Tandon, 2013). Therefore, the application of amendments for soil improvement may contribute to nutrient use efficiency. Murtaza et al. (2017) reported a significant variation in nitrogen use efficiency in saline-sodic soil in a rice-wheat cropping system. They found that the application of 100 kg N ha^{-1} with 50% soil gypsum requirement recorded the highest partial factor productivity; and that the application of 130 kg N ha^{-1} and 100% soil gypsum requirement had the highest agronomic use efficiency of nitrogen in both rice and wheat. Yaduvanshi (2003) reported the positive effect of green manure application and farm yard manure on nitrogen and phosphorus recovery in reclaimed saline sodic soil in a rice-wheat cropping system. They reported that the addition of green manure of *Sesbania* @ 4.2 t ha^{-1} with 60 kg N, 13 kg P, and 21 kg K ha^{-1} had significantly improved N recovery; and that application of *Sesbania* @ 4.2 t ha^{-1} with 120 kg N, 26 kg P, and 42 kg K ha^{-1} had recovery efficiency of 52.8% in wheat. In another study, Barbieri et al. (2006) reported that out of the total nitrogen applied in tall wheatgrass (*Elytrigia elongate*), recovery efficiency was 23–41% in the 1st year and 67–69% in the second year in sodic soil. They suggested the split application of nitrogen and the use of nitrogen sources other than urea as a strategy to reduce losses. At the same time, the response of different treatments for the correction of soil degradation problems in terms of improving nutrient use efficiency and water use efficiency is mentioned in **Table 9**. The significance of soil biological degradation in terms of increasing the population of disease-causing pathogens is significantly reducing the efficiency of different resources through their influence on crop growth and yield. Oerke (2006) reported that in the world, crop yield loss due to all major pest and diseases, such as weeds, for wheat, rice, maize, potato, soybean, and cotton was 28.2, 37.4, 31.2, 40.3, 26.3, and 28.8%, respectively, from 2001 to 2003. The loss due to insect–pest in India for cotton, rice, oilseed, pulses, groundnut, and wheat were 30, 25, 20, 15, 15, and 5%, respectively, out of their total production (Dhaliwal et al., 2010). The loss in yield ultimately remains as the natural and artificial resources applied unutilized, which may be lost by one or other pathways thereby reducing their efficiency as well as may cause pollution or degradation of soil and other natural resources.

NOVEL AGRONOMIC AND INNOVATIVE SOIL MANAGEMENT APPROACHES FOR IMPROVING SOIL HEALTH

Diversification of Nutrient Sources

The nutrient need of plant is catered by soil inherent supply or externally applied plant nutrients through organic sources, inorganic sources, and microbial inoculants. Along with the supply of nutrients, these externally applied sources of plant nutrition had varied impacts on soil properties, and may be positive or negative. The monotonous use of any one source (especially chemical fertilizers) over a long duration may change soil properties to an extent that leads to making soil ill. The use of chemical fertilizers is getting movement because of quick response, easy availability on subsidized rate, and a significant increase in crop yield, leading to higher economic gain in early year of availability; while during the latter part, the inability of other sources to cater to the need of plant nutrition, intensification of cropping systems to cater to the need of growing human and cattle population and decreasing availability, along with the increased cost of other sources of plant nutrition such as animal waste, are major reasons for the monopoly of chemical fertilizers. These nutrients supplied through chemical fertilizers remain available for a short period of time because of their property of changing chemical nature, and may get lost from the scene along with moving water. The imbalance in the use of these fertilizers and lack of attention for fertilization of secondary nutrients, such as sulfur, and micronutrients, *viz*. Fe and Zn, lead to their widespread deficiency (Tandon, 2013). This all leads to multi-nutritional deficiency and varied levels of soil degradation (Section Issues Related With Soil Health).

At present, the selection of nutrient source should be such that it provides multiple nutrients for higher yield, has considerable residual effects, and positive influence on soil properties, thereby on soil health and less on environmental footprints. This all will be difficult to achieve through a single source of nutrition. At the same time, the economy of crop nutrition may be improved through partly replacement of chemical fertilizers with other on-farm sources or cost-effective off-farm resources. The sources of crop nutrition, which helps in maintaining or improving soil health along with providing nutrition, are agro-industrial wastes, minerals without processing, green and brown manures, weed manures, and bio-fertilizers. The diversification of nutrient sources toward more responsiveness to soil health is constrained by the availability of highly subsidized chemical fertilizers and their quick, significant, and positive impact on crop production, lack of sufficient organic sources of nutrition, as well as their logistic and on-point availability, less contribution of other sources (microbial inoculation and mineral wastes) to crop nutrition. These sources along with their impact on soil health are discussed below.

Green and Brown Manures

The growth of leguminous plants and their *in-situ* trampling at the flowering stage by tillage (plowing) or incorporation of leaves and young twigs of plants collected from another area is called green manuring. The significance of using of green manuring crops has been recognized long ago (Pieters, 1927) for its capacity to provide nitrogen (Yang et al., 2018) and enhance soil organic carbon (Ramesh and Chandrasekaran, 2004); while its multifarious effects on crop production (Fageria, 2007; Valadares et al., 2016) and their quantification in various crops and locations are getting movement afterward. The use of green manuring is more common in rice-based cropping systems and, again, in lowland or irrigated rice ecosystems (Pooniya et al., 2012). Brown manuring is a co-culture of *Sesbania* and rice, in which after 40–50 days of sowing, *Sesbania* is knocked down by a spray of herbicide (2,4-D). It is more common in upland rice and reported for its potential for controlling weeds in direct seeded rice (Gangaiah and Prasad Babu, 2016; Maitra and Zaman, 2017). The significance of green and brown manuring in soil health improvement reported by different authors is summarized in **Table 10**. All these reports indicate that both green and brown manuring have a significant and positive effect on soil health along with their contribution to yield improvement and saving on the application of chemical fertilizers. At the same time, green manure has an immense potential to be an important source of crop nutrition in organic farming, which is getting momentum in India. Green manure crops occupy the land for 40 to 55 days during which one productive crop can be raised. At the same time, sufficient water in the soil is needed for proper decomposition and release of nutrients for present season crops, which is a major constraint in rainfed agriculture. Additional cost is incurred in the purchase of seeds and the application of nutrients to green manure crops (phosphorus application) and knockdown of brown manure crops. These are the weak points that make green or brown manuring difficult to be adopted by farmers on a large scale.

Use of Crop Residue and Agro-Industrial Waste

Arable crop production occupies the largest area out of the gross cropped area under cultivation as compared with other crops, such as horticultural crops. Considering the harvest index of arable crops and the nutrient composition of these residues (Sadh et al., 2018), these may be the potential options for the diversification of nutrient sources in agriculture. At the same time, most of the wastes generated from agriculture are voluminous and will add a large amount of organic carbon in soil, which is a backbone of different processes. Another important fact about crop residue is that a large part remains unutilized in cereal-based cropping systems in irrigated areas; while in

TABLE 9 | Effects of soil degradation on nutrient and water use efficiency.

Sl. No.	Crop	Soil degradation related problem	Major findings	References
1.	Rice	Soil acidity	Improvement in partial factor productivity and agronomic nitrogen use efficiency due to combined application of NPK (60:30:30 kg NPK ha^{-1}) + farm yard manure (10 t ha^{-1}) and NPK + compost (2.5 t ha^{-1})	Ghosh and Devi, 2019
2.	Rice	Soil acidity	Application of recommended rate of primary nutrients (120, 30, and 60 kg ha^{-1} N, P, and K, respectively) and addition of compost (4 t ha^{-1}) leads to improvement in water use efficiency under upland condition	Halim et al., 2018
3.	Rice and wheat	Nutrient mining and imbalance due to blanket recommendation and farmer practice of imbalance use of fertilizers	Improvement in partial factor productivity, agronomic use efficiency, recovery efficiency and nutrient harvest index of phosphorus and potassium due to optimum fertilization which was decided by considering the soil indigenous supply, yield target and crop nutrient demand.	Singh et al., 2014
4.	Rice	Saline sodic soil	Water use efficiency (1.2 and 1.16 kg m^{-3}) and water utilization efficiency (0.86 and 0.88 kg m^{-3}) was significantly higher with application of irrigation at 6 day interval and gypsum application @ 9.5 t ha^{-1}.	Hafez et al., 2015

rainfed farming, due to a large number of competitive uses, it is not available as a nutrient source. The logistic and policy initiative for residue utilization as a source of crop nutrition, blending of different crop residues to enhance nutrient content and faster release of nutrients and location-specific identification, and promotion of cost-effective processes for converting crop residues into suitable forms to be used as a source of nutrition are the thrust area for promoting the use of crop residues as a source of nutrition. The amount of crop residues generated in India from major crops is given in **Figure 1**. At the global level, residues produced from six major crops (rice, wheat, barley, sugarcane, maize, and soybean) is 3.7 Pg (billion tons) dry matter $year^{-1}$ (Bentsen et al., 2014); while Lal (2005) reported 3.8 Pg $year^{-1}$ residue production. The use of crop residues as a source of crop nutrition will be a win-win situation, as it helps to reduce the unutilized waste for agriculture, and their contribution to pollution and footprint, and success in diversifying chemical fertilizer-dominated nutrient management strategies. The co-culture of legumes in cereal-dominated cropping systems, changing nutrient management strategies by accounting the nitrogen need for *in-situ* decomposition of high C:N ratio crop residue, increased the availability of seeding machines in residue retention and adapting harvesting techniques that maintain a sufficient amount of residues in the soil at marginal farms need to be considered as options to attract stakeholders toward utilization of crop residues as a potential option for crop nutrition. In the case of organic farming, there is a need for such options as the use of *in-situ* organic sources of nutrition will be more cost-effective than purchased organic sources of nutrition considering increasing prices of off-farm organic sources of nutrition. Out of the total crop residue generated, the share of cereal crops is highest, which have a higher C:N ratio and takes longer time for decomposition and causes immobilization of soil nitrogen; while other crop residues have competitive uses. Crop residues infected with pests and diseases may increase the inoculums for the infection of the crop in the succeeding growing season.

In addition to the above-discussed unprocessed crop residues, residues are also generated while making crop produce suitable for consumption like processing and value addition of crop produce. Major residues from the processing industry include sugarcane factory waste (bagasse, pressmud, and molasses), waste from rice and wheat milling industry, waste from the fruit and vegetable processing industry, waste from the edible and non-edible oil extraction industry, waste generated during the marketing of perishable commodities, and food wastage. The use of agro industrial waste is constrained by the fact that part residues generated from these agro-industries have more economical competitive uses and therefore remain unavailable to be used as a source of nutrient; while part of unutilized residues needs some treatment before being utilized as a crop nutrient source. Information of such pre-treatments and facilities at the community or individual farmer level will be helpful for enhancing their utilization. Another difficulty is associated with the logistics of such agro-industrial waste on account of their large volume.

The significance of using crop residues and agro-industrial wastes in soil health is listed as follows:

- improvement in soil organic carbon content;
- serves as the food and fuel for microbial diversity, and also help in enriching the population diversity of desirable microbes in soil;
- help in reducing the impact of soil physical degradation processes because of positive impact on soil physical properties such as soil aggregation and infiltration rate;
- soil organic carbon enhances the cation exchange capacity, base saturation, and chelation of micronutrients, buffering pH, thereby enhancing soil chemical health;
- and improves soil chemical health through the process of decomposing soil pollutants, which is also fastening by increasing soil organic carbon.

Use of Minerals and Mineral Waste

The restricted supply of micronutrients is a common constraint for plant growth worldwide, especially in organic farming systems where nutrient supply to crops mostly depends on

TABLE 10 | Effects of green and brown manuring on soil health.

Sl. No.	Name of crop	Practice	Impact on soil health	References
1.	Maize	Green manuring (*Orychophragmus violaceus*) followed by three different level of recommended dose of nutrients (100, 85, and 75%;recommended rate nutrient application is 225, 49, and 94 kg N, P, and K, respectively)	The incorporation of green manuring crop adds 21.5–94 kg nitrogen, 2.2–9.8 kg phosphorus and 21.2–99.2 kg potassium per ha; The improvement in microbial biomass *N*, dissolved organic *N* and mineral *N* in 0–20 cm soil depth at third and eighth leaf fully expanded stage	Yang et al., 2018
2.	Rice-rice cropping system	Growing of green manuring crop either in fallow or as intercropping at 4:1 ratio as additive series without changing rice geometry	Gradual build-up of soil organic carbon as well as improvement in fulvic acid and humic acid in soil due to incorporation in *Sesbania rostrata* Berm.	Ramesh and Chandrasekaran, 2004
3.	Rice	Cultivation of *Sesbania aculeata* and *Crotalaria juncea* following by incorporation and transplanting of rice	Improvement in soil organic carbon and available nitrogen and phosphorus due to incorporation of both green manure crops	Singh et al., 2009b
4.	Rice-wheat cropping system	Incorporation of green manure crop before puddling in rice	Improvement in soil physical properties such as soil aggregation, decrease in bulk density, increase in saturated hydraulic conductivity, saturation percentage and macro-pores, reduction in soil strength, increase in infiltration rate due to incorporation of green manure crops	Ray and Gupta, 2001
5.	Rice-wheat cropping system	Incorporation of green manure crops (*Sesbania rostrata*, *Sesbania aculeata* and green gram residue before puddling in rice)	Improvement in organic matter and total soil nitrogen; reduction in bulk density by 0.03 to 0.07 Mg m^{-3} in 0–15 cm depth and 0.05 to 0.09 Mg m^{-3} in 15–30 cm soil depth; higher mean weight diameter and saturated hydraulic conductivity; improvement in root length density of rice and wheat due to incorporation of green manure crops	Mandal et al., 2003
6.	Rice based cropping system (Rice-rice-fallow; Rice-rice-milk vetch; Rice-rice-rapeseed and rice-rice-ryegrass)	Sowing of green manure crop after harvesting of second season rice crop and incorporating by plowing before sowing of nextrice crop	Green manure significantly improve phosphatase and urease activity	Qaswar et al., 2019
7.	Rice	Direct seeded aerobic rice + brown manuring of *Sesbania* followed by no till wheat	Increase in soil total nitrogen, soil organic carbon, soil microbial biomass carbon and microbial biomass nitrogen	Nawaz et al., 2016
8.	Rice	Direct wet seeded rice	Positive effect on soil health through nutrient cycling as *Sesbania aculeata* accumulate 32.4 kg N, 3.65 kg P, and 16.0 kg K per ha without any fertilizer addition in its biomass which become easily available to rice	Gangaiah and Prasad Babu, 2016
9.	Rice-rapeseed cropping system	Tillage system involving conventional tillage (residue removal) and no tillage with residue retention; Brown manuring of cowpea and mulching of *Gliricidia* in both tillage system	Brown manuring of cowpea and mulching of *Gliricidia* produce more soil organic carbon pool, carbon sequestration rate and carbon retention efficiency	Yadav et al., 2019
10.	Rice-wheat cropping system	Direct seeding of rice with brown manuring followed by wheat in sodic soil of Indo-Gangetic region	Increase in soil organic carbon and microbial biomass carbon due to brown manuring	Mishra et al., 2015
11.	Rice–mustard cropping system	Zero till direct seeded rice + brown manuring followed by zero till mustard (residue retention of both crops)	Improvement in soil quality index (SQI) over conventionally followed puddled transplanted rice followed by conventionally till mustard. The SQI was calculated based on saturated hydraulic conductivity, pH, total nitrogen, available phosphorus and available potassium.	Das et al., 2021
12.	Rice	Combination of brown manuring with herbicide (pre-emergence application of butachlor, pendimethalin, pretilachlor and benthiocarb) in direct seeded rice	Enhancement in partial factor productivity of nitrogenous, phosphatic and potassic fertilizer added there by reducing their contribution to soil and groundwater pollution	Maity and Mukherjee, 2009
13.	Rice-wheat cropping system	Study of effect of green manure crops (*Sesbania aculeata*, *Leucaena leucocephala*, cowpea and mungbean green manure crops on soil zinc and copper content (for 3 years in rice-wheat cropping system)	Positive effect on soil zinc and copper status after 3 year due to incorporation of green manure crops.	Mishra et al., 2006a

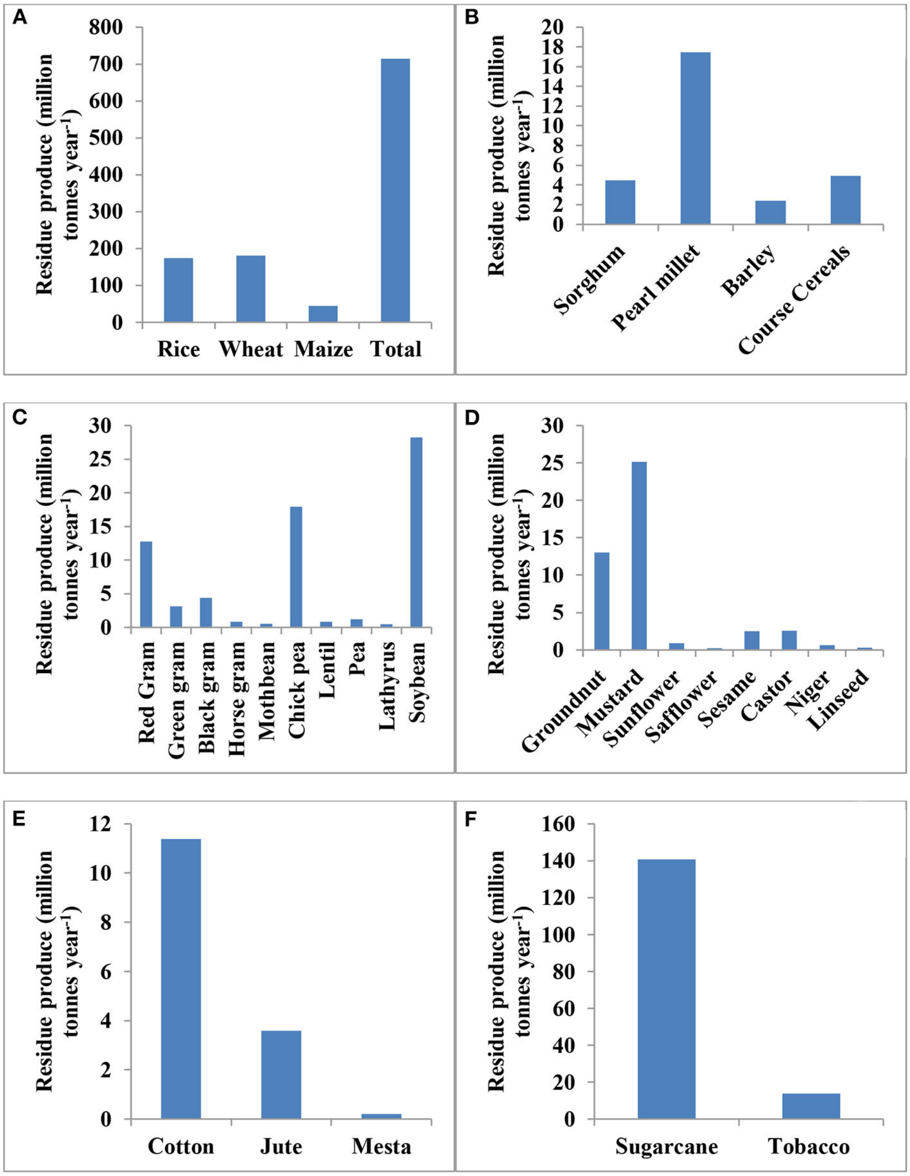

FIGURE 1 | Residue production from different crops in India **(A–F)** (Anonymous, 2019).

the mineralization of native soil organic matter, decomposition of applied manures, and crop residues. Based on a laboratory incubation study conducted for 140 days to investigate the potential release of copper (Cu), manganese (Mn), and zinc (Zn) from the rock mineral flour (RMF), the results showed that about 4.6% of Cu added as RMF was released irrespective of the quantity of the RMF applied. Zn release from RMF increased from 5.8 to 15.5%, with an increase in the amount of RMF applied (Shivay et al., 2010). These results showed that RMF could be used to meet Cu, Mn, and Zn requirements of organically grown cereals. The use of minerals as a source of crop nutrition without any chemical processing (Kulasekaran et al., 2015) is getting highlighted, and their significance can be explained as follows:

- inability of organic resource to fulfill the need for crop nutrition at present production requirement;
- identification of microbial processes and availability of microbial cultures for enhancing the nutrient availability from minerals making the mineral matter available form;
- availability of mineral waste generated by different processing industries and problem of their disposal;
- increased cost of processing of minerals to make chemical fertilizers and dependence on import of raw material for preparation of chemical fertilizers;
- availability of large amount of mineral, which is unsuitable to be used as raw material for preparation of chemical fertilizers (Kumari and Phogat, 2008);

- suitability of minerals in raw form in specific situation such as suitability of rock phosphate in acidic soil (Sharma and Prasad, 2003);
- and despite the above-mentioned positive impacts on soil health, there are several constraints that make the use of mineral waste difficult. The amount of heavy metals present in minerals and their availability to crop, logistics of voluminous raw minerals, and awareness of the processes and conditions making minerals a suitable source of crop nutrition are the primary hurdles that need to be addressed in making use of minerals in agriculture a suitable option for diversification of nutrient sources.

The low nutrient content, slow release of minerals due to longer time required for disintegration, less change of acting as a non-point source of pollution, lower cost of by-product of processing industry such as basic slage and phosphogypsum., and capacity to work as complimentary and supplementary sources of crop nutrition in organic farming are the other points that need to be considered in making mineral and mineral waste a possible alternative for diversification of nutrient sources.

The positive effects of these on soil health include:

- enhance the soil mineral composition from a crop production point of view thereby increasing the soil inherent nutrient supplying capacity;
- enhance the population and diversity of desirable microbes that are needed for biogeochemical cycling of nutrients in soil;
- and reduce the adverse effect of chemical fertilizer-generated abnormalities on soil properties.

Use of Weeds as Manures

The weed being unwanted plants and categorized as biotic stress can be harvested and used as manure. The weed plants as a composite group generally had a higher concentration of nutrients as compared with crop plants. The important points to be considered while using weeds as manure in crop cultivation are as follows:

- Weeding is generally done during early growth, leading to low dry matter accumulation and thereby lower nutrient accumulation in them.
- Not a viable option of nutrient diversification after seed formation, as it again creates a problem in the next year.
- If precautions are taken, such as using pre-emergence herbicides and following proper cultural measures, then the population and dry matter generated would be very minimal.
- The weeds are composite flora and because of the diversity of species with respect to time and space dimension, it becomes difficult to quantify the expected amount of the nutrients added by weeds.
- At the same time, weeds compete with crop plants and absorb nutrients supplied for crop plants, thereby affecting their growth.
- Some species of weeds have an allelopathic effect on crop plants while decomposing their residue. This may affect the growth of crop plants.
- Weeds grown during the fallow period help in conserving soil moisture and also reduce losses in the fertile top soil layer. This will help in maintaining soil fertility.
- Other positive effects of weeds manures on soil health are the same as those of the addition of crop residues through organic matters.

Adaptation of Modern Tillage System (Minimum/ Zero Tillage, Stubble Mulch Tillage)

The conventional plow tillage involves physical manipulation of soil; therefore, it has several implications on soil health that can be seen primarily on soil physical health, soil biological health, and lastly on soil chemical health. The major objective of conventional plow-based tillage is managing weeds along with preparing of seedbeds with required soil physical properties. Due to the availability of an alternative strategy for weed management (herbicides) and maintaining soil physical condition suitable for sowing of crops without tillage, the present plow-based tillage system is molding to a new form, which is collectively called conservation tillage. The other reasons responsible for the emergence and adoption of the conservation tillage system include the adverse effect of plow-based tillage on soil degradation through erosion and fading organic carbon, increasing prices of energy (petroleum) required for tillage operation, government policy orientation in developed countries during early days, problem of disposal of crop residue in intensive cereal-based cropping systems, short time availability for field preparation in intensive cropping systems, availability of tillage equipment for seeding with least disturbance to soil and in layer of crop residue, and positive effect of conservation tillage in various combinations of resource conservation technology.

The conservation tillage system is based on three major principles, *viz.* continuous or minimal mechanical soil disturbance, maintenance of a permanent biomass soil mulch cover on the ground surface, and diversification of crop species (Kassam et al., 2019). It consists of different forms such as zero tillage, minimum tillage, and stubble mulch tillage. The positive effect of this tillage system on soil health is indicated by the three above-mentioned principles of conservation agriculture, and increasing area under conservation tillage indicates economic gain either in tangible or non-tangible forms by stakeholders. The health improvements achieved by following the conservation tillage system are listed below:

- Reduction in the rate of soil erosion through wind and water action, which can be achieved because of a reduction in erodibility.
- Increase in soil organic carbon as a minimum 30% of surface covered with crop residue is the principle of the conservation tillage system.
- Enhance the microbial population and diversity, soil microbial biomass carbon and nitrogen, and soil microbial enzymatic activities of microorganisms because of the availability of organic matters as their food.
- Improvement in major soil physical parameters such as water holding capacity, soil aggregation, infiltration rate,

porosity, bulk density, and soil strength, thereby making soil physically healthy.
- Added crop residues are a source of multiple plant nutrients and therefore enhance the chemical health of soil.
- Soil chemical properties such as temperature moderation, buffering soil pH, nutrient holding capacity, and ion exchange capacity are positively affected by conservation tillage.
- Some hurdles in the adoption of the conservation tillage-based system include competitive uses of crop residues, immobilization of nitrogen during residue decomposition, acting of crop residues as a hibernating material for crop pests and diseases causing pathogen, build-up of termite population, reduced crop germination, and difficulty in manure and fertilizer application.
- The third principle of CA (crop species diversification) can reduce the extraction of nutrients from the same soil layer, and if fertility restorer crops (such as legumes and grasses) are included in the cropping system, then it will have positive and beneficial effects on soil health.
- Maintaining crop residues also helps in correcting soil root zone salinity because of reduced evaporation losses.

Enhancing Soil Microbial Diversity (Use of PGPR and Microbial Consortia, Use of Biocontrol Agents)

There are two possible ways to enhance soil microbial diversity. The first one is the direct addition of microbial culture and the other is the enhancement of the inherent soil microbial population by providing a suitable environment for microbial growth. The direct improvement of soil microbial diversity was started with the use of biofertilizers (microbial inoculation having the capacity of nutrient acquisition/ fixation) for nitrogen fixation. The possible options for enhancing microbial diversity are as follows:

- Use of microbial cultures that have a capacity for nutrient acquisition and fixation.
- Use of microbial cultures that have an antagonistic interaction with disease-causing microorganisms and deleterious rhizobacteria.
- Use of microbial cultures that fasten the rate of organic matter turnover (Choudhary et al., 2016).
- Use of microorganisms that secrete growth-promoting hormones such as auxin (Zahir et al., 2004).
- Use of microbes that have a capacity to fasten the decomposition residue of agrochemicals or soil pollutants (soil security; Nayak et al., 2018).

The indirect ways for enhancing microbial population diversity include:

- Using organic sources of crop nutrition as per availability and economic consideration in varied combinations of chemical fertilizers.
- Changing tillage system from conventional plow-based to conservation tillage.
- Use of soil amendments for correcting soil reactions as a pH range near neutral is suitable for different types of microbial growth and processes.
- Crop diversification with place for legumes and forage crops. Legume crops secrete a large amount of carbon material through their roots, and their rhizosphere is rich in microbial diversity (Kumar et al., 2018). Forage crops, such as Napier grass, produce a large amount of root biomass; while growing of berseem was reported to have a positive effect on soil physical and chemical properties.
- Following harvesting methods that maintain at least part of above-ground plants on the soil surface.
- Irrigation management practices for modification of soil microclimates suitable for microbial growth that include drainage of excess water, creation and utilization of irrigation facility from rain water or water from above ground or below ground reservoirs, and irrigation for reducing soil salinity.
- Increasing the use of resource conservation technologies such as green and brown manuring, use of organic mulches and different land configurations such as permanent beds.

There are certain lacunae that make it difficult to adopt the direct methods of enhancing soil microbial population, and include low economic gain and less visibility of crop growth and yield improvement due to their uses, the growth and population build-up is affected by soil environment and weather condition, higher sensitivity to agrochemicals, and their availability in pure form without admixture of any other material. The indirect options of enhancing soil microbial diversity have economic bias; hence, their uniform and wider implications in the favor of enhancing the soil health remain frozen.

Positive Effects of Microbial Enhancement on Soil Health

The impact of improvement in microbial diversity on soil health is overlapped by the impact of diversification of nutrient sources, as both are interdependent on their capacity to improve soil health. The crop residue serves as a raw material for microbial activities; while microbes are important agents for decomposition or turnover of diversified nutrient sources. Some of the additional positive effects of enhancing soil microbial diversity are as follows:

- Enhancing soil microbial diversity fastens the decomposition of agrochemicals and other harmful plant secretions, thereby making soil pollution free.
- Short term storage of plant nutrition through the process of immobilization, thereby reducing losses in plant nutrients.
- Helps in reducing the population of soil-borne disease-causing microorganisms because of antagonistic interaction and competition for same natural resources.
- Improves soil chemical health by increasing the share of fixed forms of nutrients in crop nutrition. This is most prominently seen in the case of phosphorus, as the use efficiency of phosphorus applied through soluble chemical fertilizers hardly exceeds 15–20% (Roberts and Johnston, 2015; Prasad et al., 2018); while most of the phosphorus remains in the soil in a fixed form.

Efficient Resource Cycling Through Integrated Farming System

In the urge of an ambitious project of doubling the income of farmers in India, several agricultural interventions have to play an integrated role (Anonymous, 2018a). One such option suggested to achieve this target is curtailing the cost of purchased resources through the generation and use of on-farm resources and their recycling or multiple uses in production systems. This is possible through the integrated farming system (IFS) approach involving the integration of more than one enterprise complementing the main enterprise (which is most of the time a cropping system). As this resource cycling through IFS is linked with economic gain, it can be smoothly adopted by farmers, and soil health improvement through this option is complimentary with the involvement of very less monetary inputs.

The possible options for soil health improvement through resource recycling in IFS are:

- Incorporation of small animals and birds (poultry) with higher liquidity of capital (as the investment on feed and space is less and for short time). These animals can be reared on on-farm inputs, and their excreta are a boon to soil health improvement.
- Installation of crop by-product enrichment plants such as vermi-composting unit and composting unit.
- Installation of a biogas unit and use of slurry as manure (it reduces methane emission from direct application of biomass).
- Planting of leguminous plants such as *Leucana leucocephala*, *Gliricidia*, which can serve as green manuring crops.

The integrated farming system has a positive effect on soil due to the followings reasons:

- The efficient cycling of by-products reduces wastage and enhances the biogeochemical cycling of plant nutrition, which is the basis of soil chemical health.
- The final by-products after multiple uses (such as use of crop residue for cattle feed or for mushroom production or for vermi-composting) of the resources have a retained and sometimes even enhanced nutritional value, which can be a valuable soil amendment.
- The complementary interaction between natural resources and different enterprises helps in making a closed system of nutrient cycling. This ultimately helps in enhancing the sustainability of the system.

Marginal farm area, difficulty in marking of small produce, complex interactions among enterprises, difficulty at farmer level to have expertise in all enterprises, lack of awareness on the positive interactions among enterprises, low risk-bearing ability, and capital investment are the major bottlenecks of implementing IFS-based systems.

Soil Health Improvement in Problem Soil (Through Use of Soil Amendments, and by Crop Cultivation Practices and Phytoremediation)

Problematic soils in India mainly consist of salt-affected soil and acidic soil with an area extension of 6.73 million ha (Sharma et al., 2016) and 15.93 million ha, respectively. However, at the global level, 0.34 billion and 0.56 billion ha of the area have saline and sodic soil, respectively (Shahid et al., 2018). Along with this, there are soils that are getting polluted because of untreated industrial effluents, sewage water and waste from landfill areas, and seepage of industrial pollutants. These soils have several problems and need special management practices and input addition along with normal management practices for successful crop production. These practices are broadly divided as follows.

Use of Soil Amendments and Its Effect on Soil Health

Soil amendments are mainly added to bring the soil reaction to the desirable range, thereby improving soil health. Considering soil reactions, exchangeable sodium percentage and electrical conductivity of the soil are broadly classified as saline, sodic (alkali), and saline-sodic (alkali) soil. Saline soil is dominated by soluble salts such as sulfate and sodium chloride; while the dominant salt in sodic soil is sodium carbonate. In the case of saline soil, the leaching of soluble salts below the root zone with plenty of fresh water is followed. Along with that, limestone and iron pyrite are chemical soil amendments that can be added. In the case of sodic soil, gypsum, sulfur, iron sulfate, and iron pyrite may be added to improve the soil condition. The improvement for acidic soil is done by liming with calcium oxide, calcium hydrate, dolomite, calcite, or basic slag.

The application of soil amendments for the correction of sodic soil has a significant and positive effect on soil health through improvement in soil properties such as aggregation, porosity, and infiltration rate, replacing exchangeable sodium concentration from exchange complexes and bringing the pH in the neutral range. In acidic soil, the application of liming materials leads to a reduction in the toxic concentration of metal elements such as Fe, Mn, and Al, enhancement of the availability of phosphorus, calcium, magnesium, and potassium, and enhancement of the activity and diversity of microbes in the soil. These improvements in soil health make the soil fit for crop cultivation.

Cultivation Practices

Along with the addition of soil amendments, cultivation practices are also reported to be beneficial for the management of problematic soil. These are as follows:

Soil Tillage

Deep plowing in order to increase infiltration of rainfall moisture to a considerable depth, compartmental bunding, which increases the opportunity time for infiltration of rainwater and opening of a dead furrow, which acts as a drainage channel during an event of heavy rainfall and stores moisture, are suggested modifications.

Land Configuration

Land leveling, which reduces depression spots where water gets collected and there may be an accumulation of salts and different land configurations such as ridges and furrows, and sowing of crop ¾ height of ridges are also suggested for efficient crop cultivation in problematic soils.

Selection of Crops, Mulching, and Irrigation

Crops tolerant of saline soil such as mustard, barley, cotton, and sugar beet (Jehangir et al., 2013) are suggested; while for sodic/alkali soil, Karnal grass, para grass, rhodes grass, rice, sugar beet, and green manure crops such as dhaincha (*Sesbania aculeata*) are suggested (Chhabra, 1996). Other suggested measures are the application of excessive water during pre-sowing irrigation for leaching of salts, frequent and shallow irrigation, use of fresh quality irrigation water, and use of organic mulches to reduce evaporation losses, which will reduce the upward movement of salts.

All these cultivation practices improve soil physical properties and promote soil microbial population and diversity, which ultimately contribute to soil health improvement. The addition of organic matters due to the growing of crops, application of mulches, and suitable microclimate provided by irrigation help in increasing microbial population, thereby improving soil biological health.

Phytoremediation

It is defined as the use of higher plants for the cost effective, environmental-friendly rehabilitation of soil and groundwater contaminated by toxic metals and organic compounds (Aken, 2011). Phytoremediation plays a role in soil health improvement through its capacity to combat soil pollution. It is achieved by phytoextraction (phytoaccumulation), phytovolatilization, phytostabilization, or phytodegradation (Yan et al., 2020). This strategy is important for heavy metal pollutants, organic pollutants, industrial effluents, sewage water, waste for landfills used as manure, etc. Nowadays, phytoremediation is essential as town compost and waste water from cities is increasingly used in agriculture in peri-urban areas mainly for the growing of vegetables and flowers. Therefore, these areas have polluted soil that needs to be reclaimed in a cost-effective way. At the same time, the use of agrochemicals is now a regular practice and is increasing day by day because of changes in the level of biotic stresses and the need to produce more from limited resources. Therefore, soil pollution is going to be an important reason for soil degradation in times to come. Some of such situations are observed in parts of India where soil ground water is becoming polluted because of the excessive use of agrochemicals (Kaur and Kaur, 2019). Considering this, it has become essential to incorporate the phytoremediation strategy in agricultural production systems. Besides pollution in agricultural land, areas for dumping of waste are increasing at an alarming rate (Kumar et al., 2017; Kiran et al., 2020), and they will act as a source of contaminants for agriculturally useful land in the future, and these are areas within the scope of phytoremediation. Another important consideration for the phytoremediation technique is that it does not show any significant effect on crop growth and development in the short term, but it helps in improving soil health by reducing the adverse effect of pollutants on human and animal health.

Mimicry of Natural Ecosystem in Agro-Ecosystem for Soil Health Improvement

An agroecosystem is a natural ecosystem modified for the production of different provisional services (Hodgson, 2012), and it is characterized by both planned and unplanned diversities (Power, 2013). It differs from a natural ecosystem in terms of low species and genetic diversity, open system of nutrient cycling, simple and linear tropical interaction, and, most importantly, it heavily depends on human interference for its different functions (Odum, 1969). All of these make an agroecosystem fragile, leading to concern about its sustainability. Along with it, several types of human-induced land degradation (Sections Soil Physical Degradation to Soil Ecosystem Services) add to the instability of agroecosystems. On the other hand, natural ecosystems have several types of self-regulating and self-sustaining functions having the potential to be used in agroecosystems. Studying such functions and identifying the optimum niche of agroecosystems for their successful incorporation in agroecosystems is called mimicking the natural ecosystem. According to Dore et al. (2011), the incorporation of certain characteristics of natural ecosystems into agroecosystems would improve some properties of agroecosystems, such as productivity, stability, and resilience, and that could be considered as mimicry of agroecosystems. This mimicry of natural ecosystems needs to have an economic bias along with improving long-term sustainability for higher adoption at the used end. For the successful implementation of mimicry of natural ecosystems in agroecosystems, Dore et al. (2011) mentioned certain steps, which are listed below:

- Selection of functions that agronomists wish to improve.
- Identification, in natural ecosystems, of characteristics modifying these functions (diversity, microclimate, soil microbes interaction).
- Definition of qualitative and quantitative relationships linking properties and functions (slash and burn cultivation).
- Transposition of these functions to agricultural conditions.
- Use of these functions for the design of agroecosystems with specified aims.
- Checking that the new agroecosystems express the targeted functions and have no undesirable properties.

Along with this, the concept of ecological intensification (Tottonell, 2014) of agriculture also found a sustainable strategy and had a positive impact on soil health. The options for mimicking natural ecosystems with economic consideration include diversification of cropping systems, crop intensification in space and time dimensions (mixed or inter cropping and crop rotation), residue incorporation, less disturbance to soil (changing tillage system to zero or minimum tillage), multi-storied cropping, and many more. The concept of conservation agriculture, organic farming, integrated farming systems, and groups of resource conservation technologies are parallel with the concept of mimicry of natural ecosystems. Therefore, the positive effect of mimicry of natural ecosystems on soil health will be the same as that of the effect of the above-mentioned technology.

Alternative Agriculture (Agroforestry) for Soil Health Management of Marginal Land

Along with the strategy for reducing the degradation of agricultural land, a suitable strategy for the management of already severely degraded land or marginal land unsuitable for regular cultivation is the need of hours. At the global level, the extent of degraded land has been reported from <1 billion to as high as 6 billion ha (Gibbs and Salmon, 2015). Further, degraded land can be realized by seeing the land use pattern of India, which shows that 17.47 million ha of the area have barren and un-culturable lands and 13.24 million ha of the area have culturable waste lands (Anonymous, 2019). The areas are hardly suitable for regular cultivation of arable crops and if desired, then additional management practices are required, which may not be economical. A suitable economical alternative for restoration of such areas is possible through alternative agriculture such as agroforestry (Anonymous, 2018b). The food and agricultural organization define agroforestry as a collective name of land use systems and technologies where woody perennials are deliberately used on the same land management units as agricultural crops and/or animals, in some form of special arrangement or temporal sequence. The system is self-sustaining because of the involvement of diversified components such as arable crops, forage species, tree components, and domestic animals, with three basic systems, *viz.* agrisilviculture, silvopastoral, and agrisilvopastoral. The positive effects of agroforestry on soil health are as follows:

- The tree component of agroforestry protects soil from erosion through an extensive root network and large canopy. It is also helpful in stabilizing gullies and preventing their spread. At the same time, it produces a large amount of woody matter if retained over a longer duration and can be claimed as carbon credit.
- The grass component involved in agroforestry helps conservation of soil against erosion due to thick cover on ground and also enhances soil organic carbon. This leads to reduction in land degradation.
- Leguminous tree and shrubs species such as *Acacia Senegal* (L) Willd., *Cajanuscajan* L., *Gliricidia sepium*, *Sesbania sesban*, and *Tephrosia spp*., enrich the soil through biologically fixed nitrogen along with the addition of organic matter through leaf fall (Ribeiro-Barros et al., 2018). This will help enhance soil biological health.
- As a self-sustaining system, agroforestry is a cost-effective option for the management of soil health on degraded and waste land, with additional income through wood and fodder produced.
- The areas along field boundaries, farm roads, or canals that remain barren and severely affected by one or other types of land degradation will also be suitable for one or other components of agroforestry. This leads to enhanced biodiversity of cultivated farms, thereby enhancing the soil health of farms as a whole.
- The agroforestry system, as a whole, generates several functions that will help in biogeochemical nutrient cycling with the active involvement of biosphere components such as plants and microorganisms.

CONCLUSIONS

In the present day, soil no more remains a medium for plant growth but it turns into a valuable resource for mankind to meet its requirement of provisional services from plants and animals receding in agroecosystems. Considering the present level of land degradation, there is a need to develop and implement novel approaches to maintain soil health with a similar or even higher level of production from agroecosystems. Concepts such as diversification of nutrient sources with emphasis on the use of organic manures and other alternatives to compliment and supplement the chemical fertilizer-based approach will have the potential to contribute significantly to the improvement of soil health. The diversification of production systems through the adoption of conservation agriculture and organic farming is worth considering their role in soil health improvement. The closed system of nutrient cycling achieved through an integrated farming system, will be the self-sustained option of soil health management, along with improvement in resource use efficiency. There is a need to give attention to soil biological health, with the involvement of attempts to enhance soil microbial diversity and curtailment of soil pollution caused by the extensive use of agrochemicals (such as chemical fertilizers).

AUTHOR CONTRIBUTIONS

AS has prepared the first draft of the manuscript. YS have conceptualized and edited the manuscript. Both authors contributed to the article and approved the submitted version.

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