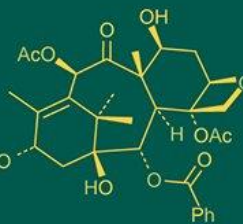
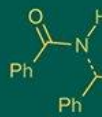


International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2026): 5.29
IJABR 2026; SP-10(6): 1417-1427
www.biochemjournal.com
Received: 23-05-2026
Accepted: 25-06-2026

Lily Chauhan

Department of Forest Products
and Utilization, Mahatma
Gandhi Udyanikee Evam
Vanikee Vishwavidyalaya,
Durg, Chhattisgarh, India

Rajesh Kumar

Department of Forest Products
and Utilization, Mahatma
Gandhi Udyanikee Evam
Vanikee Vishwavidyalaya,
Durg, Chhattisgarh, India

Lakhan Singh Rajput

Department of Forest Products
and Utilization, Mahatma
Gandhi Udyanikee Evam
Vanikee Vishwavidyalaya,
Durg, Chhattisgarh, India

Gunjan Verma

Department of Forest Products
and Utilization, Mahatma
Gandhi Udyanikee Evam
Vanikee Vishwavidyalaya,
Durg, Chhattisgarh, India

Corresponding Author:**Lily Chauhan**

Department of Forest Products
and Utilization, Mahatma
Gandhi Udyanikee Evam
Vanikee Vishwavidyalaya,
Durg, Chhattisgarh, India

Nutrient dynamics and fertility constraints in entisols: A critical review

Lily Chauhan, Rajesh Kumar, Lakhan Singh Rajput and Gunjan Verma

DOI: <https://www.doi.org/10.33545/26174693.2026.v10.i6Sq.8848>

Abstract

Entisols are young, weakly developed soils widely distributed across river floodplains, coastal belts, arid and semi-arid regions, and recently deposited alluvial landscapes. Despite their agricultural importance in supporting cereals, pulses, oilseeds, vegetables, and plantation crops, these soils are highly fragile because of low organic matter content, poor aggregation, weak nutrient-retention capacity, and high susceptibility to erosion and nutrient losses. The present review critically examines the distribution, formation, physical and chemical characteristics, nutrient dynamics, fertility constraints, and sustainable management strategies associated with entisols under diverse agroecological conditions. The review was developed through analysis of published scientific literature, research reports, and soil fertility studies related to nutrient transformations and soil management practices in entisols. Findings revealed that nutrient dynamics in entisols are strongly controlled by soil texture, parent material, climate, pH, organic carbon, and management practices. Nitrogen losses through leaching, volatilization, and denitrification are common due to coarse texture and low cation exchange capacity, whereas phosphorus availability is restricted by fixation reactions involving iron, aluminum, and calcium compounds. Potassium and sulfur deficiencies frequently occur because of high leaching losses, while zinc and iron deficiencies are common in alkaline and calcareous entisols. Continuous cultivation, excessive tillage, residue removal, and imbalanced fertilizer use further accelerate soil fertility decline. The review highlights that integrated nutrient management, organic amendments, conservation agriculture, biofertilizers, residue recycling, and precision nutrient management significantly improve nutrient-use efficiency, soil health, and climate resilience. Sustainable management of entisols is therefore essential for maintaining long-term productivity, ecological stability, and agricultural sustainability under changing climatic conditions.

Keywords: Entisols, nutrient dynamics, soil fertility, nutrient leaching, micronutrients, integrated nutrient management.

Introduction

Entisols are among the youngest and least developed soil orders in the USDA Soil Taxonomy system and are characterized by minimal profile development and weak horizon differentiation (Soil Survey Staff, 2014; Buol *et al.*, 2011) ^[10]. These soils are formed under conditions where soil-forming processes are either recently initiated or continuously interrupted by erosion, flooding, sediment deposition, or climatic instability (Bhardwaj *et al.*, 2024) ^[6]. Because of their immature nature, entisols show considerable variation in physical and chemical properties depending on parent material, climatic conditions, vegetation, and topography (Brady & Weil, 2017; Bargah *et al.*, 2025a) ^[2, 9]. Globally, entisols are distributed across river floodplains, coastal sandy regions, glacial deposits, mountainous areas, volcanic terrains, and arid desert ecosystems (Buol *et al.*, 2011) ^[10]. In India, they occupy significant agricultural areas in the Indo-Gangetic plains, coastal regions, Rajasthan deserts, and deltaic landscapes where they support cultivation of several food and cash crops (Sehgal, 1996; ICAR, 2015; Bargah *et al.*, 2025b) ^[3]. Soil fertility forms the foundation of sustainable agricultural production, ecosystem functioning, and environmental stability. Fertile soils regulate nutrient cycling, water retention, carbon sequestration, and biological productivity while supporting food security and ecological resilience across diverse agroecosystems (Bhardwaj *et al.*, 2023) ^[7]. Among the twelve soil orders recognized under the USDA Soil Taxonomy system, entisols represent one of the youngest and least developed soil groups because of minimal horizon differentiation And weak pedogenic development (Brady and Weil, 2016) ^[9]. These soils are formed under conditions where soil-forming processes are either weak or continuously interrupted by erosion, flooding,

Sediment deposition, wind action, or unstable geomorphic activities (Buol *et al.*, 2011; Chandra *et al.*, 2021) ^[10, 11]. Globally, entisols occupy nearly 16–18% of the ice-free land surface and are distributed extensively in river floodplains, coastal regions, deserts, glacial deposits, steep slopes, and recently deposited alluvial landscapes (Kumar *et al.*, 2022a) ^[31, 32, 34, 35]. Agriculturally, entisols are important because they are intensively cultivated for cereals, pulses, oilseeds, sugarcane, vegetables, and horticultural crops (Lal & Stewart, 2019; Chandra *et al.*, 2024) ^[12, 41]. However, these soils are generally considered fragile due to low organic matter content, poor aggregation, weak nutrient retention, and high susceptibility to erosion and nutrient depletion (Havlin *et al.*, 2016; Darro *et al.*, 2022) ^[13, 19]. Sandy texture and low cation exchange capacity result in rapid nutrient leaching, particularly of nitrogen and potassium (Brady & Weil, 2017) ^[9]. Continuous cultivation and excessive tillage further accelerate degradation of soil structure and fertility (Khandekar *et al.*, 2024) ^[27]. Nutrient dynamics in entisols are strongly influenced by environmental factors such as climate, irrigation, cropping systems, and management practices (Fageria, 2012) ^[15]. Nitrogen losses through leaching and volatilization are common, while phosphorus availability is often restricted by fixation reactions (Havlin *et al.*, 2016) ^[19]. Micronutrient deficiencies, especially zinc and iron deficiencies, are frequently observed in alkaline entisols (Alloway, 2008; Kumar *et al.*, 2024b) ^[29]. In India, entisols constitute a major soil resource across the Indo-Gangetic alluvial plains, Rajasthan desert ecosystems, coastal belts, river basins, and semi-arid sandy regions where they support important agricultural activities such as cereal cultivation, oilseed production, horticulture, agroforestry, and grazing systems (Kumar *et al.*, 2025) ^[25]. Despite their agricultural importance, entisols are generally categorized as fragile and low-fertility soils because of low organic matter content, poor structural development, weak aggregate stability, low nutrient-retention capacity, and high susceptibility to erosion and nutrient losses (Havlin *et al.*, 2017; Limanpure and Kumar, 2018) ^[19, 36, 42]. The coarse-textured nature of many entisols contributes to low cation exchange capacity (CEC), rapid water infiltration, poor moisture retention, and limited nutrient buffering capacity, which collectively reduce nutrient-use efficiency and crop productivity (Kumar *et al.*, 2022b) ^[31, 32, 34, 35]. Understanding nutrient transformations and fertility limitations in entisols is essential for developing sustainable management strategies (Srinivasarao *et al.*, 2014). Integrated nutrient management, organic amendments, residue recycling, conservation tillage, and precision nutrient management are increasingly recognized as effective approaches for improving soil productivity and sustainability (Lal, 2020) ^[39, 40]. Therefore, this review aims to provide a comprehensive understanding of nutrient dynamics, fertility constraints, and management strategies associated with entisols under diverse agroecological conditions (Kumar and Ramchandra, 2018b) ^[36]. Soil organic matter is a critical determinant of nutrient dynamics, soil aggregation, microbial activity, and moisture

conservation. However, entisols generally contain low soil organic carbon because of rapid organic matter decomposition, poor vegetation cover, limited biomass incorporation, and unstable environmental conditions (Lal, 2015; Kumar *et al.*, 2022c) ^[31, 32, 34, 35, 39, 40]. Low organic carbon adversely affects microbial biomass, enzymatic activity, aggregate stability, nutrient retention, and nutrient-use efficiency. Declining soil organic matter further weakens resilience against climatic stresses such as drought and temperature fluctuations. Climate change has emerged as an additional threat to the sustainability of entisol ecosystems. Rising temperatures, erratic rainfall patterns, prolonged droughts, and extreme weather events significantly alter nutrient transformation processes and accelerate nutrient losses (Kumar *et al.*, 2022d) ^[31, 32, 34, 35]. High-intensity rainfall events enhance nutrient leaching, runoff, and soil erosion, whereas drought stress suppresses microbial activity, nutrient mineralization, and plant nutrient uptake (Lal, 2020; Mandwa *et al.*, 2024) ^[40, 43]. Water and wind erosion remove nutrient-rich topsoil and contribute to desertification, fertility decline, and land degradation, particularly in arid and semi-arid ecosystems (Morgan, 2005; Kumar *et al.*, 2023) ^[33]. Salinity and sodicity problems are also intensifying in irrigated and coastal entisols due to rising temperatures, evaporation, and poor-quality irrigation water.

2. Distribution and formation of entisols

Entisols are widely distributed across different climatic and geomorphological regions of the world and are considered one of the most extensive soil orders in recently deposited or weakly weathered landscapes (Table 1 & Fig. 1) (Brady & Weil, 2017) ^[9]. These soils are commonly found in river valleys, coastal plains, glacial outwash areas, sand dunes, mountainous terrains, and arid regions where active erosion or sediment deposition prevents the development of mature soil horizons (Buol *et al.*, 2011) ^[10]. In tropical and subtropical regions, entisols frequently occur along river floodplains where periodic flooding deposits fresh alluvium (Jenny, 1941; Pandey *et al.*, 2018) ^[26, 49]. In arid and semi-arid environments, limited rainfall and sparse vegetation reduce weathering intensity, resulting in poor horizon development (Foth, 1990) ^[18]. Coastal entisols are generally sandy and highly permeable, whereas alluvial entisols may exhibit relatively better fertility because of continuous deposition of mineral-rich sediments (Sehgal, 1996; Singh *et al.*, 2024). Physically, entisols are generally coarse-textured with sandy or loamy sand textures, weak aggregation, low water-holding capacity, and high permeability. Such physical properties enhance nutrient movement beyond the root zone and increase susceptibility to drought stress (Brady and Weil, 2016) ^[9]. Chemically, these soils are characterized by low cation exchange capacity, low soil organic carbon, and poor nutrient reserves. Soil reaction varies depending on parent material and environmental conditions, ranging from acidic to alkaline. Biologically, entisols often contain low microbial biomass and reduced enzymatic activity because of

insufficient organic substrates and unstable environmental conditions (Paul, 2015; Kumar *et al.*, 2024a) ^[29]. In India, entisols occupy significant agricultural landscapes across the Indo-Gangetic alluvial plains, coastal belts, deltaic regions, desert areas of Rajasthan, and foothill regions of the Himalayas (Table 2 & Fig. 2) (ICAR, 2015). These soils are especially important in floodplain agriculture because they support cultivation of rice, wheat, maize, sugarcane, pulses, and vegetables (Lal & Stewart, 2019) ^[41]. In coastal regions, entisols are used for coconut, cashew, and plantation crops. Despite their agricultural importance, productivity of these soils is frequently limited by nutrient deficiencies, salinity, erosion, and poor moisture retention (Havlin *et al.*, 2016) ^[19]. The formation or pedogenesis of entisols is strongly

influenced by parent material, climate, vegetation, relief, and time (Jenny, 1941; Singh *et al.*, 2022) ^[26]. Since these soils are geologically young, they exhibit minimal profile differentiation and lack well-developed subsurface horizons (Soil Survey Staff, 2014). Parent materials such as alluvium, coastal sand, volcanic ash, and weathered rock fragments play a major role in determining soil texture, mineral composition, and nutrient status (Buol *et al.*, 2011; Tiwari *et al.*, 2024) ^[10]. Continuous deposition, erosion, and flooding interrupt soil-forming processes, thereby restricting the development of mature horizons. Consequently, entisols often display considerable variability in fertility, structure, and water-holding capacity depending on local environmental conditions (Brady & Weil, 2017) ^[9].

Table 1: Distribution of entisols in the world

Region/Country	Major Areas of Occurrence	Dominant Landscape	Agricultural Importance	Key Constraints	Citation
India	Indo-Gangetic Plains, Rajasthan, Coastal belts, Deltaic regions	Alluvial plains, deserts, coastal sands	Rice, wheat, sugarcane, pulses, vegetables	Nutrient leaching, low organic matter	Sehgal (1996); ICAR (2015); Lal & Stewart (2019) ^[41]
China	Yellow River Basin, coastal plains	Floodplains and alluvial deposits	Cereals and intensive agriculture	Soil erosion and nutrient imbalance	Buol <i>et al.</i> , (2011); Brady & Weil (2017) ^[9,10]
USA	Mississippi floodplains, coastal plains	River valleys and sandy soils	Maize, soybean, cotton	Erosion and low moisture retention	Soil Survey Staff (2014); Brady & Weil (2017) ^[9]
Australia	Arid interior and coastal sands	Desert and sandy landscapes	Grazing and dryland farming	Salinity and drought stress	FAO (2015); Buol <i>et al.</i> , (2011) ^[10]
Brazil	Amazon floodplains and coastal zones	Recent alluvial deposits	Plantation crops and soybean	Nutrient depletion	Lal & Stewart (2019); Brady & Weil (2017) ^[9, 41]
Egypt	Nile delta and river floodplains	Alluvial river deposits	Wheat and horticulture	Salinity and alkalinity	FAO (2015); Havlin <i>et al.</i> , (2016) ^[19]
Sudan	Semi-arid floodplains	Sandy alluvial soils	Millet and sorghum	Moisture stress and erosion	Buol <i>et al.</i> (2011); Lal (2020) ^[10, 41]
Pakistan	Indus basin floodplains	Alluvial landscapes	Wheat, cotton, rice	Salinity and nutrient losses	FAO (2015); Brady & Weil (2017) ^[9]
Bangladesh	Deltaic floodplains	Riverine sediments	Rice-based systems	Flooding and nutrient depletion	ICAR (2015); Lal & Stewart (2019) ^[41]
Nigeria	Savannah and river valleys	Sandy and alluvial soils	Maize and cassava	Low fertility and erosion	Buol <i>et al.</i> , (2011); Havlin <i>et al.</i> , (2016) ^[10, 19]

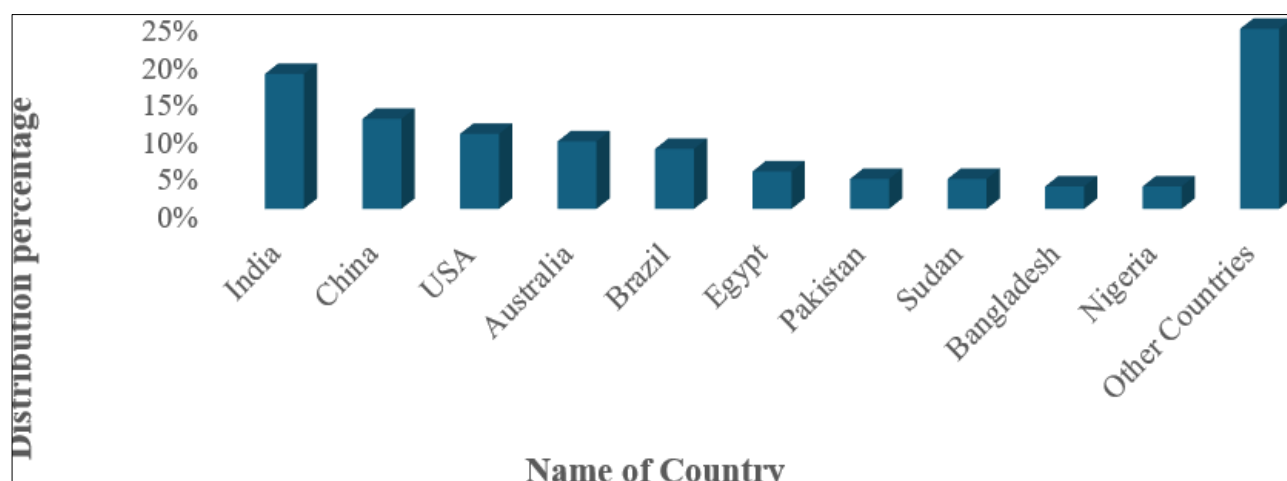
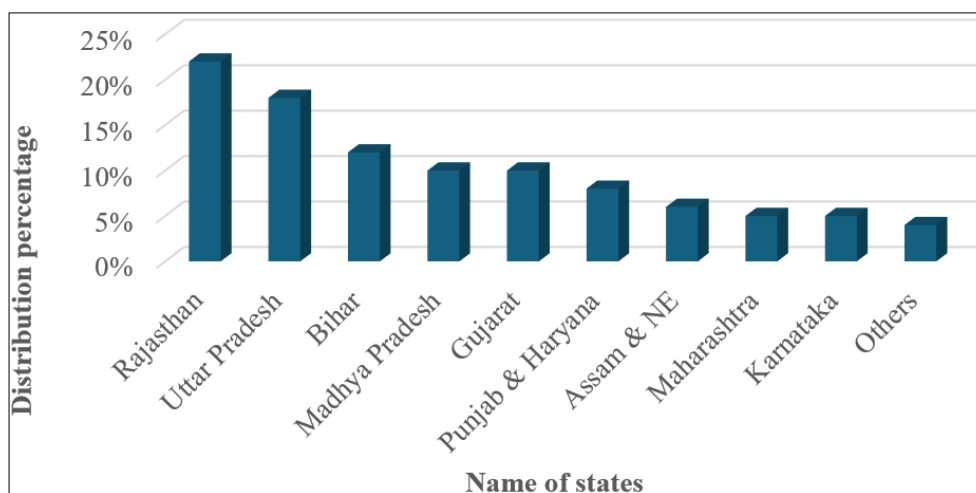


Fig 1: Distribution percentages of entisols in different countries.

Table 2: Status and distribution of entisols in India

Parameter	Status of Entisols in India	Major Regions/States	Citation
Total geographical coverage	Entisols occupy approximately 28.08% of India's total geographical area	Widely distributed across India	ICAR–NBSS&LUP; Soil Survey Staff (2014)
Total area under Entisols	About 92.13 million hectares	Indo-Gangetic Plains, Rajasthan, coastal belts	NBSS&LUP Publication No. 94
Major landscapes	Recent alluvial plains, river floodplains, coastal sands, desert regions	Uttar Pradesh, Bihar, Punjab, Rajasthan, Gujarat	Brady & Weil (2017); Buol <i>et al.</i> , (2011) ^[9, 10]
Dominant texture	Sandy to loamy sand	Rajasthan desert, coastal Tamil Nadu, Gujarat	Havlin <i>et al.</i> (2016); Foth (1990) ^[18, 19]
Fertility status	Generally low organic carbon and low nutrient retention	Arid and semi-arid regions	Srinivasarao <i>et al.</i> , (2014); Lal (2020) ^[40]
Major nutrient deficiencies	Nitrogen, phosphorus, zinc, and iron deficiencies common	Alkaline and calcareous entisols	Alloway (2008); Fageria (2012) ^[1, 15]
Important crops grown	Rice, wheat, sugarcane, maize, pulses, vegetables	Indo-Gangetic plains and deltaic regions	Lal & Stewart (2019) ^[41]
Major constraints	Nutrient leaching, erosion, moisture stress, salinity	Rajasthan, coastal and irrigated regions	Havlin <i>et al.</i> , (2016); Lal (2020) ^[19, 40]
Soil reaction (pH)	Acidic to alkaline depending on parent material	Coastal and alluvial regions	Brady & Weil (2017) ^[9]
Management requirement	Integrated nutrient management and conservation agriculture	Nationwide	Fageria (2012); FAO (2015) ^[15]

**Fig 2:** Status and distribution of entisols in India

3. Physical characteristics of entisols

The physical properties of entisols play a crucial role in determining nutrient dynamics, soil fertility, moisture availability, and crop productivity (Hillel, 2004) ^[20]. Because these soils are weakly developed and geologically young, they generally exhibit poor structural organization and considerable variability in texture and porosity (Buol *et al.*, 2011) ^[10]. The physical characteristics of entisols are strongly influenced by parent material, climate, topography, and land-use practices (Table 3) (Brady & Weil, 2017) ^[9]. In many regions, entisols are dominated by sandy or coarse-textured particles, which significantly affect water retention, nutrient-holding capacity, aeration, and root development (Foth, 1990; Soni *et al.*, 2025) ^[18]. These soils are commonly associated with low aggregation and weak structural stability due to insufficient clay and organic matter content (Havlin *et al.*, 2016) ^[19]. Texture is one of the most important physical properties controlling nutrient dynamics in entisols. Sandy entisols exhibit rapid drainage and high infiltration rates, which increase nutrient leaching losses, particularly of nitrogen and potassium (Brady & Weil, 2017) ^[9]. Coarse-textured soils also possess low surface area and low cation exchange capacity, thereby reducing the soil's ability to retain essential nutrients. In contrast, loamy entisols may have comparatively better moisture retention

and nutrient availability. However, even loamy entisols often suffer from poor aggregation because of low organic carbon content (Srinivasarao *et al.*, 2014; Netam *et al.*, 2025). Soil structure in entisols is generally weak and poorly developed (Foth, 1990) ^[18]. Lack of stable aggregates reduces root penetration and microbial activity while increasing susceptibility to erosion (Lal, 2020; Shukla *et al.*, 2025a) ^[40]. Continuous tillage and low biomass return further degrade soil structure and contribute to compaction. Bulk density is often moderate to high, especially in intensively cultivated areas, which may restrict root growth and reduce soil aeration (Hillel, 2004) ^[20]. Poor pore continuity and low organic matter also negatively affect infiltration and water movement. Water-holding capacity is generally low in entisols because of coarse texture and limited humus content (Lal & Stewart, 2019) ^[41]. Consequently, crops cultivated on these soils frequently experience drought stress during dry periods. Low moisture retention also affects nutrient uptake efficiency and microbial activity. In addition, entisols are highly vulnerable to both wind and water erosion, especially under sparse vegetation cover and improper management practices (Lal, 2020) ^[40]. Erosion removes nutrient-rich topsoil and accelerates soil degradation.

Table 3: Physical characteristics of entisols

Physical Property	Characteristics in Entisols	Effect on Soil Behaviour and Fertility	Citation
Soil profile development	Very weak or absent horizon development; generally A horizon over C horizon	Indicates immature soil with low pedogenic development	USDA Soil Survey Staff (2014); Soil Genesis and Classification (2011)
Soil texture	Ranges from sandy to loamy sand; some loam in alluvial zones	Sandy texture increases leaching and reduces nutrient retention	Brady & Weil (2017); Havlin <i>et al.</i> (2016) ^[9, 19]
Structure	Weak, single-grained or massive structure	Poor aggregation leads to erosion susceptibility and low root anchorage	Brady & Weil (2017); Foth (1990) ^[9, 18]
Bulk density	Moderate to high, especially in cultivated sandy soils	Restricts root penetration and reduces aeration in compact zones	(Hillel, 2004) ^[20] ; Brady & Weil (2017) ^[9]
Porosity	High macroporosity but poor pore continuity in sandy entisols	Rapid drainage and low water retention efficiency	Lal (2020); Foth (1990) ^[18, 40]
Water-holding capacity	Very low due to sandy texture and low organic matter	Frequent drought stress and low nutrient uptake efficiency	Lal & Stewart (2019); Brady & Weil (2017) ^[9, 41]
Permeability / infiltration	Very high infiltration rate in sandy entisols	Enhances nutrient leaching (N, K, S losses)	Havlin <i>et al.</i> (2016); Brady & Weil (2017) ^[9, 19]
Erodibility	High susceptibility to wind and water erosion	Loss of topsoil and nutrient-rich surface layer	Lal (2020); Morgan (2005) ^[40]
Colour	Light brown to pale yellow in sandy areas; darker in alluvial zones	Reflects low organic matter content in most entisols	USDA Soil Survey Staff (2014)
Moisture regime	Highly variable; drought-prone in sandy regions, periodically flooded in Fluvents	Controls microbial activity and nutrient cycling	Buol <i>et al.</i> , (2011); Brady & Weil (2017) ^[9, 10]
Depth	Often shallow to moderately deep depending on parent material	Limits root development in shallow entisols	USDA Soil Survey Staff (2014)
Compaction susceptibility	Moderate; increases under continuous cultivation	Reduces infiltration and root growth	(Hillel, 2004) ^[20] ; Lal (2020) ^[40]

4. Chemical characteristics of entisols

Chemical properties of entisols strongly influence nutrient availability, soil fertility, microbial activity, and crop productivity. Due to weak profile development and low organic matter accumulation, these soils generally exhibit poor nutrient retention and low fertility status. The chemical composition of entisols varies considerably depending on parent material, climatic conditions, vegetation, and land-use systems. Important chemical characteristics include soil pH, organic carbon content, cation exchange capacity (CEC), electrical conductivity (EC), and nutrient availability (Table 4). These parameters collectively determine nutrient transformations and fertilizer use efficiency in entisols (Najdenko *et al.*, 2024; Yadav *et al.*, 2025)^[46]. Soil pH in entisols ranges from acidic to alkaline depending on climatic conditions and mineral composition. Entisols occurring in humid regions are often acidic because of intense leaching of basic cations, whereas those in arid and semi-arid regions are generally alkaline or calcareous. Soil pH significantly affects nutrient solubility and microbial processes. Under acidic conditions, phosphorus fixation by iron and aluminum compounds becomes dominant, while alkaline conditions reduce the availability of micronutrients such as

zinc, iron, manganese, and copper (Hou *et al.*, 2020; Niharika & Takankhar, 2025)^[21, 47]. Organic carbon content in entisols is generally low due to rapid decomposition, low biomass accumulation, and poor residue incorporation. Low organic matter negatively affects nutrient retention, aggregate stability, microbial activity, and moisture conservation. Since organic matter acts as a reservoir of nutrients, its deficiency limits nitrogen mineralization and reduces overall soil fertility. Similarly, low clay and humus content contribute to reduced cation exchange capacity, thereby limiting the soil's ability to retain positively charged nutrients such as calcium, magnesium, potassium, and ammonium (Singh *et al.*, 2020; Bouhia *et al.*, 2022)^[8]. Electrical conductivity is usually low in well-drained entisols, but salinity problems may develop in coastal and irrigated regions due to salt accumulation. Salinity adversely affects nutrient uptake, osmotic balance, and plant growth. Nutrient availability in entisols is often constrained by rapid leaching, low organic matter, and unfavorable pH conditions. Nitrogen and phosphorus deficiencies are common, while micronutrient deficiencies such as zinc and iron frequently occur in alkaline soils (Huang *et al.*, 2020; Niharika & Takankhar, 2025)^[22, 47].

Table 4: Chemical characteristics of entisols

Chemical Property	Characteristics in Entisols	Effect on Fertility	Citation
Soil pH	Acidic to alkaline depending on parent material and climate	Influences nutrient availability and microbial activity	Hou <i>et al.</i> , (2020); Niharika & Takankhar (2025) ^[21, 47]
Organic carbon	Generally low due to weak horizon development and poor organic matter accumulation	Poor nutrient retention and low microbial activity	Singh <i>et al.</i> , (2020); Bouhia <i>et al.</i> , (2022) ^[8]
CEC	Usually low, especially in sandy entisols	Reduced nutrient holding capacity	Huang <i>et al.</i> , (2020) ^[22]
Electrical conductivity	Variable; saline conditions may occur in irrigated and coastal regions	Salinity stress and poor nutrient uptake	Najdenko <i>et al.</i> , (2024) ^[46]
Nitrogen availability	Commonly low because of low organic matter content	Poor crop growth and chlorosis	Yadav <i>et al.</i> (2025)
Phosphorus availability	Often limited due to fixation and low native fertility	Reduced root development	Phuyal & Nair (2025) ^[50]
Micronutrient status	Zn and Fe deficiencies are common in alkaline entisols	Chlorosis and low productivity	Soil Properties and Microelement Availability Review (2025)

5. Nutrient dynamics in entisols

Nutrient dynamics in entisols are highly complex and are influenced by soil texture, mineral composition, climate, organic matter content, microbial activity, and management practices (Brady & Weil, 2017) ^[9]. Because entisols are weakly developed and coarse-textured, they generally possess low nutrient retention capacity and high nutrient mobility (Havlin *et al.*, 2016) ^[19]. Nutrient transformations such as mineralization, immobilization, nitrification, denitrification, adsorption, fixation, and leaching play important roles in determining nutrient availability for crop growth (Fageria, 2012) ^[15]. Understanding nutrient dynamics is therefore essential for improving fertilizer efficiency and maintaining long-term soil fertility in entisols (Srinivasarao *et al.*, 2014).

5.1 Nitrogen dynamics

Nitrogen is one of the most limiting nutrients in entisols because of its high mobility and susceptibility to losses through leaching, volatilization, and denitrification (Havlin *et al.*, 2016) ^[19]. Organic matter decomposition releases ammonium ions through mineralization, which are subsequently converted into nitrate through nitrification processes mediated by soil microorganisms (Brady & Weil, 2017) ^[9]. Since nitrate ions are highly soluble, they are easily leached beyond the root zone under excessive rainfall or irrigation conditions. Sandy entisols with high infiltration rates are therefore particularly vulnerable to nitrogen losses (Foth, 1990) ^[18]. Ammonia volatilization also contributes to nitrogen depletion, especially under alkaline soil conditions and surface application of urea fertilizers (Fageria, 2012) ^[15]. Under waterlogged conditions, denitrification processes convert nitrate into gaseous nitrogen forms, thereby reducing nitrogen availability to crops. Poor organic matter content further limits nitrogen storage and mineralization capacity in entisols. Consequently, nitrogen-use efficiency in these soils is generally low, requiring split fertilizer applications and integrated nutrient management strategies for sustainable crop production (Havlin *et al.*, 2016) ^[19].

Low soil organic carbon further restricts microbial-mediated nitrogen mineralization processes. Studies have shown that continuous use of inorganic nitrogen fertilizers without organic amendments accelerates nutrient depletion and soil degradation in entisols (Srinivasarao *et al.*, 2019). Integrated nutrient management practices involving farmyard manure, compost, crop residues, and biofertilizers significantly improve nitrogen retention, microbial activity, and nutrient-use efficiency.

5.2 Phosphorus dynamics

Phosphorus dynamics in entisols are primarily controlled by adsorption, precipitation, and fixation reactions (Fageria, 2012) ^[15]. Although phosphorus is less mobile than nitrogen, its availability is often restricted because of chemical fixation in soil. In acidic entisols, phosphorus reacts with iron and aluminum oxides to form insoluble compounds, whereas in alkaline soils it precipitates with calcium compounds (Havlin *et al.*, 2016) ^[19]. These fixation processes reduce phosphorus availability to plants despite fertilizer application.

Soil pH strongly influences phosphorus solubility and plant uptake. Maximum phosphorus availability generally occurs near neutral pH conditions (Brady & Weil, 2017) ^[9]. Low

organic matter content and weak microbial activity in entisols also reduce phosphorus mineralization from organic residues. Furthermore, coarse-textured entisols possess limited phosphorus buffering capacity, making phosphorus management highly important for sustaining crop productivity (Srinivasarao *et al.*, 2014).

Organic amendments improve phosphorus availability by reducing fixation and stimulating microbial activity. Phosphate-solubilizing bacteria also enhance phosphorus availability by converting insoluble phosphates into plant-accessible forms (Richardson *et al.*, 2009).

5.3 Potassium dynamics

Potassium exists in soil solution, exchangeable, non-exchangeable, and mineral forms (Tisdale *et al.*, 1993). In entisols, potassium dynamics are significantly influenced by clay mineralogy, texture, and leaching processes. Sandy entisols generally possess low exchangeable potassium because of weak adsorption sites and low cation exchange capacity (Havlin *et al.*, 2016) ^[19]. Consequently, potassium losses through leaching are common, particularly in high-rainfall environments.

Potassium availability is also affected by weathering of primary minerals such as feldspars and micas (Brady & Weil, 2017) ^[9]. However, because entisols are geologically young, the extent of mineral weathering varies considerably depending on parent material. Continuous cropping without balanced potassium fertilization gradually depletes soil potassium reserves and negatively affects crop productivity (Fageria, 2012) ^[15].

5.4 Sulfur dynamics

Sulfur is an essential secondary nutrient involved in protein synthesis, enzyme activity, and chlorophyll formation (Havlin *et al.*, 2016) ^[19]. In entisols, sulfur dynamics are largely controlled by organic matter content and sulfate mobility. Sulfur is mainly present in organic forms, which are mineralized by soil microorganisms into sulfate ions available for plant uptake (Brady & Weil, 2017) ^[9]. Because sulfate ions are highly mobile in coarse-textured soils, sulfur leaching losses are common in sandy entisols.

Low organic matter and intensive cultivation often reduce sulfur reserves in entisols, resulting in sulfur deficiency symptoms such as chlorosis and reduced plant growth (Fageria, 2012) ^[15]. Sulfur management through gypsum application, organic amendments, and balanced fertilization is therefore important for maintaining crop productivity.

5.5 Micronutrient dynamics

Micronutrient availability in entisols is strongly influenced by soil pH, organic matter content, redox conditions, and parent material composition (Alloway, 2008) ^[1]. Zinc, iron, manganese, and copper are among the most important micronutrients affecting crop growth and metabolism. In alkaline entisols, zinc and iron deficiencies are particularly common because high pH reduces their solubility and plant availability (Brady & Weil, 2017) ^[9]. Iron chlorosis is frequently observed in calcareous soils where bicarbonate ions interfere with iron uptake.

Organic matter plays a significant role in micronutrient retention and chelation (Fageria, 2012; Singh *et al.*, 2025) ^[15]. Low organic carbon levels therefore reduce micronutrient availability and increase deficiency risks. Excessive phosphorus fertilization may also induce zinc

deficiency due to nutrient antagonism. Sustainable micronutrient management involving soil application, foliar sprays, and organic amendments is essential for maintaining balanced nutrition and crop productivity in entisols (Alloway, 2008)^[1].

6. Major fertility constraints in entisols

Entisols are considered inherently fragile soils because of their poor nutrient retention capacity, weak structural stability, low organic matter content, and high susceptibility to erosion and nutrient depletion (Brady & Weil, 2017; Buol *et al.*, 2011)^[9, 10]. These soils often face multiple fertility-related problems that severely limit agricultural productivity and sustainability. The major fertility constraints in entisols are associated with rapid nutrient losses, moisture stress, salinity, micronutrient deficiencies, and degradation caused by continuous cultivation. Since most entisols possess sandy to loamy texture with minimal horizon development, they are unable to efficiently retain water and nutrients, thereby reducing fertilizer use efficiency and crop response (Lal & Stewart, 2019)^[41].

6.1 Low Organic matter

Low organic matter content is one of the most serious fertility constraints in entisols (Srinivasarao *et al.*, 2014). Rapid decomposition of plant residues under high temperature conditions and inadequate addition of organic biomass reduce soil organic carbon accumulation. Since organic matter serves as a reservoir of nutrients and improves soil structure, its deficiency adversely affects nutrient retention, aggregation, microbial activity, and moisture-holding capacity (Fageria, 2012)^[15]. Low organic carbon also limits nitrogen mineralization and reduces soil biological activity, thereby negatively affecting nutrient cycling and crop growth (Brady & Weil, 2017)^[9].

6.2 Nutrient leaching

Nutrient leaching is another major problem in entisols, particularly in coarse-textured sandy soils with high infiltration rates (Havlin *et al.*, 2016)^[19]. Nitrogen, potassium, sulfur, and other soluble nutrients are highly susceptible to downward movement beyond the root zone during rainfall or excessive irrigation. Such nutrient losses reduce fertilizer use efficiency and increase production costs. Nitrate leaching may additionally contaminate groundwater resources and create environmental concerns (Lal, 2020)^[40]. Poor cation exchange capacity further accelerates nutrient losses from these soils.

6.3 Soil erosion

Soil erosion is a major land degradation problem affecting entisols because of weak aggregation, sparse vegetation cover, and unstable soil structure (Lal, 2020; Mohale *et al.*, 2025)^[40, 45]. Wind erosion is especially severe in arid and semi-arid entisols, whereas water erosion dominates in sloping and high-rainfall regions. Erosion removes nutrient-rich topsoil containing organic matter, clay particles, and plant nutrients, thereby reducing soil fertility and crop productivity (Brady & Weil, 2017)^[9]. Continuous cultivation without conservation measures further aggravates soil degradation.

6.4 Moisture stress

Moisture stress is another important limitation associated with entisols due to their low water-holding capacity and rapid drainage characteristics (Lal & Stewart, 2019)^[41]. Coarse-textured entisols retain limited amounts of water, resulting in frequent drought stress during dry periods. Insufficient soil moisture restricts nutrient dissolution and root uptake, thereby reducing crop growth and yield. Water stress also negatively affects microbial activity and nutrient mineralization processes (Foth, 1990; Shukla *et al.*, 2025b)^[18].

6.5 Salinity and sodicity

Salinity and sodicity problems frequently occur in coastal and irrigated entisols where soluble salts and sodium ions accumulate in the root zone (Rengasamy, 2010). High salinity creates osmotic stress and restricts water absorption by plants, while sodicity deteriorates soil structure and reduces permeability. Salt-affected entisols often exhibit poor aeration, crust formation, and nutrient imbalance, which negatively affect crop productivity (Havlin *et al.*, 2016)^[19]. Improper irrigation and inadequate drainage further intensify salinity problems.

6.6 Micronutrient deficiencies

Micronutrient deficiencies, particularly zinc and iron deficiencies, are widespread in entisols under alkaline and calcareous conditions (Alloway, 2008)^[1]. High soil pH reduces micronutrient solubility and availability, leading to chlorosis, stunted growth, reduced enzyme activity, and lower crop yields. Deficiencies of manganese, copper, and boron may also occur depending on soil properties and cropping systems (Table 5) (Fageria, 2012)^[15]. Continuous cultivation and imbalanced fertilizer use further aggravate micronutrient depletion in these soils.

Table 5: Major fertility constraints in entisols

Fertility Constraint	Cause	Impact on Crop Growth	Citation
Low organic matter	Rapid decomposition	Poor nutrient supply	Srinivasarao <i>et al.</i> , (2014).
Nutrient leaching	Sandy texture	Low fertilizer efficiency	Lal, (2020) ^[40]
Soil erosion	Weak aggregation	Loss of fertile topsoil	Brady & Weil., (2017) ^[9]
Moisture stress	Low water retention	Reduced nutrient uptake	Lal & Stewart, (2019) ^[41]
Salinity and sodicity	Salt accumulation	Poor root growth	Havlin <i>et al.</i> , (2016) ^[19]
Zinc deficiency	High soil pH	Reduced enzyme activity	Alloway., (2008) ^[1]
Iron chlorosis	Calcareous conditions	Yellowing of leaves	Alloway., (2008) ^[1]

7. Factors affecting nutrient dynamics in entisols

Nutrient dynamics in entisols are strongly influenced by several interacting environmental and management-related factors, including climate, parent material, land-use systems,

irrigation practices, and organic matter management (Brady & Weil, 2017)^[9]. These factors regulate nutrient transformations, mobility, retention, and availability within the soil system. Because entisols are weakly developed and

highly sensitive to environmental changes, even slight alterations in management practices can significantly affect nutrient cycling and soil fertility status.

7.1 Climate

Climate is one of the most important factors controlling nutrient dynamics in Entisols (Lal & Stewart, 2019) ^[41]. Temperature and rainfall influence weathering processes, organic matter decomposition, microbial activity, and nutrient mobility. High rainfall conditions increase nutrient leaching, especially in sandy soils, leading to severe losses of nitrogen, potassium, sulfur, and other soluble nutrients (Havlin *et al.*, 2016) ^[19]. High temperatures accelerate decomposition and mineralization of organic matter, which may temporarily increase nutrient availability but eventually reduce soil organic carbon levels (Foth, 1990; Tekam *et al.*, 2025) ^[18].

7.2 Parent material

Parent material plays a major role in determining mineral composition, texture, nutrient reserve, and soil reaction (Buol *et al.*, 2011) ^[10]. Entisols derived from alluvial deposits often contain relatively higher nutrient reserves compared to sandy coastal entisols. Calcareous parent materials contribute to alkaline soil conditions that reduce availability of micronutrients such as zinc and iron (Alloway, 2008; Vaishnav *et al.*, 2025) ^[1]. Mineral weathering and clay mineralogy additionally influence potassium dynamics and nutrient retention capacity.

7.3 Land use systems

Land-use systems and cropping practices significantly affect

Nutrient cycling and soil fertility (Tisdale *et al.*, 1993). Intensive cultivation without balanced nutrient replenishment accelerates nutrient depletion and soil degradation. Continuous monocropping, excessive tillage, and residue removal reduce soil organic matter and microbial activity (Srinivasarao *et al.*, 2014). Conversely, crop rotation, cover cropping, and residue incorporation improve nutrient recycling and enhance soil fertility.

7.4 Irrigation practices

Irrigation practices strongly influence nutrient movement, leaching, and salinity development in entisols (Rengasamy, 2010). Excessive irrigation increases nutrient leaching losses and may induce waterlogging or salt accumulation in poorly drained areas. Efficient irrigation methods such as drip irrigation help conserve water and improve nutrient-use efficiency (FAO, 2013). Balanced irrigation scheduling is therefore essential for maintaining soil fertility and crop productivity.

7.5 Organic matter management

Organic matter management through application of compost, farmyard manure, green manure, and crop residues significantly improves nutrient retention and microbial activity in entisols (Srinivasarao *et al.*, 2014). Organic amendments enhance aggregation, cation exchange capacity, water-holding capacity, and biological activity (Fageria, 2012) ^[15]. Residue recycling and reduced tillage additionally help conserve soil organic carbon and reduce erosion. Sustainable nutrient management in entisols therefore depends heavily on maintaining adequate organic matter levels (Table 6).

Table 6: Factors affecting nutrient dynamics in entisols

Factors	Influence on Nutrient Dynamics	Citation
Rainfall	Increases nutrient leaching	Brady & Weil (2016) ^[9]
Temperature	Accelerates decomposition	Havlin <i>et al.</i> , (2014) ^[19]
Parent material	Determines nutrient reserve	USDA-NRCS (2014)
Cropping system	Influences nutrient cycling	Havlin <i>et al.</i> , (2014) ^[19]
Irrigation	Affects nutrient movement	FAO (2015)
Organic matter	Improves nutrient retention	Brady & Weil (2016) ^[9]
Tillage practices	Alters soil structure and fertility	Indian Society of Soil Science (2012)

8. Management strategies for improving fertility in entisols

Improvement of fertility in entisols requires integrated and sustainable management strategies because these soils are inherently low in nutrient retention, organic matter, and water-holding capacity (Havlin *et al.*, 2016) ^[19]. Efficient soil management practices are essential to minimize nutrient losses, improve soil structure, enhance microbial activity, and increase crop productivity. Modern fertility management approaches focus on combining organic amendments, balanced fertilization, conservation agriculture, and precision nutrient management to maintain long-term soil health and sustainability (Lal, 2020) ^[40].

8.1 Integrated nutrient management (INM)

Integrated Nutrient Management (INM) is considered one of the most effective approaches for managing fertility in entisols (Fageria, 2012) ^[15]. INM involves combined use of organic manures, inorganic fertilizers, crop residues, and biofertilizers to improve nutrient availability and fertilizer use efficiency. Organic amendments such as farmyard

manure, compost, green manure, and vermicompost enhance soil organic carbon, aggregation, microbial activity, and moisture retention (Srinivasarao *et al.*, 2014). These materials also improve cation exchange capacity and reduce nutrient leaching losses (Brady & Weil, 2017) ^[9]. Biofertilizers such as nitrogen-fixing bacteria and phosphate-solubilizing microorganisms contribute to sustainable nutrient supply and improve soil biological activity (Vessey, 2003). Balanced use of organic and inorganic nutrient sources therefore helps maintain long-term soil fertility and crop productivity.

8.2 Organic matter management

Organic matter management plays a central role in improving physical, chemical, and biological properties of entisols (Srinivasarao *et al.*, 2014). Application of farmyard manure (FYM), compost, crop residues, green manure, and vermicompost increases soil organic carbon and enhances nutrient retention capacity. Organic materials improve aggregate stability, infiltration, moisture conservation, and microbial activity (Fageria, 2012) ^[15]. Green manuring with

leguminous crops additionally contributes biological nitrogen fixation and improves soil fertility. Regular addition of organic residues is therefore essential for sustaining productivity in Entisols.

8.3 Conservation practices

Conservation practices are important for reducing soil erosion, conserving moisture, and improving nutrient-use efficiency in entisols (Lal, 2020) ^[40]. Mulching protects the soil surface from erosion and evaporation while improving water infiltration and temperature regulation (FAO, 2017). Cover cropping reduces nutrient losses and improves organic matter accumulation. Contour farming and strip cropping help minimize runoff and soil erosion on sloping lands. Reduced tillage practices minimize soil disturbance, conserve organic carbon, and enhance aggregate stability. Such conservation-based approaches significantly improve long-term soil health and sustainability.

8.4 Micronutrient management

Micronutrient deficiencies, particularly zinc and iron deficiencies, are common in entisols under alkaline conditions (Alloway, 2008) ^[1]. Application of zinc sulfate,

iron chelates, boron fertilizers, and foliar nutrient sprays helps correct micronutrient deficiencies and improve crop growth. Organic amendments additionally increase micronutrient availability through chelation and improved microbial activity (Fageria, 2012) ^[15]. Soil testing and balanced fertilization are essential for diagnosing and correcting micronutrient imbalances.

8.5 Precision nutrient management

Precision nutrient management involves site-specific fertilizer recommendations based on soil testing, crop requirement, and nutrient status (Havlin *et al.*, 2016) ^[19]. Modern tools such as remote sensing, GIS, sensors, and decision-support systems help improve nutrient-use efficiency and reduce environmental pollution (Subramanian *et al.*, 2015). Split fertilizer application and fertigation are especially beneficial in entisols because they minimize nutrient leaching losses and enhance nutrient availability during critical crop growth stages. Adoption of precision nutrient management therefore contributes significantly to sustainable agricultural productivity (Table 7).

Table 7: Management strategies for improving fertility in entisols

Management Practice	Benefits	Citation
Integrated nutrient management	Balanced nutrient supply	Tisdale <i>et al.</i> , (1993)
Farmyard manure application	Improves organic carbon	Brady & Weil, (2016) ^[9]
Compost and vermicompost	Enhances microbial activity	Gopal <i>et al.</i> , (2009)
Mulching	Conserves soil moisture	Lal, (2004) ^[38]
Cover cropping	Reduces erosion	FAO, (2015)
Reduced tillage	Maintains soil structure	Lal, (2004) ^[38]
Zinc sulfate application	Corrects Zn deficiency	Katyal & Randhawa, (1983)
Soil testing	Improves fertilizer efficiency	Havlin <i>et al.</i> , (2014) ^[19]

9. Role of microorganisms in nutrient cycling

Soil microorganisms play a crucial role in nutrient cycling, organic matter decomposition, mineralization, nutrient solubilization, and maintenance of soil fertility in entisols (Brady & Weil, 2017) ^[9]. Because entisols generally possess low organic matter and weak nutrient retention capacity, microbial activity becomes extremely important for sustaining nutrient availability and improving soil productivity. Soil microorganisms such as bacteria, fungi, actinomycetes, algae, and protozoa contribute significantly to biogeochemical transformations of essential nutrients including nitrogen, phosphorus, sulfur, and micronutrients (Fageria, 2012) ^[15]. Rhizobacteria are among the most important beneficial microorganisms associated with nutrient cycling in entisols. Plant growth-promoting rhizobacteria (PGPR) enhance plant growth through biological nitrogen fixation, phosphorus solubilization, phytohormone production, and suppression of soil-borne pathogens (Vessey, 2003). Nitrogen-fixing bacteria such as *Rhizobium*, *Azotobacter*, and *Azospirillum* convert atmospheric nitrogen into plant-available forms, thereby

improving nitrogen availability in nutrient-poor soils (Havlin *et al.*, 2016) ^[19]. Similarly, phosphate-solubilizing bacteria increase phosphorus availability by releasing organic acids that dissolve insoluble phosphate compounds. Mycorrhizal fungi also play a major role in improving nutrient uptake and soil health in entisols (Smith & Read, 2008). Arbuscular mycorrhizal fungi establish symbiotic associations with plant roots and enhance absorption of phosphorus, zinc, copper, and water from the soil. Mycorrhizae additionally improve plant tolerance against drought, salinity, and environmental stress conditions commonly observed in entisols. Microbial decomposition of crop residues and organic amendments contributes to mineralization and release of nutrients into the soil solution (Table 8) (Brady & Weil, 2017) ^[9]. Soil microorganisms also improve aggregate stability through production of organic binding substances that enhance soil structure and reduce erosion. Therefore, maintenance of microbial diversity through organic matter management, reduced tillage, and biofertilizer application is essential for sustaining nutrient cycling and long-term fertility in entisols.

Table 8: Role of microorganisms in nutrient cycling

Microorganism	Function in Soil	Citation
<i>Rhizobium</i>	Biological nitrogen fixation	Havlin <i>et al.</i> , (2016) ^[19]
<i>Azotobacter</i>	Nitrogen fixation	Fageria, (2012) ^[12]
Phosphate-solubilizing bacteria	Increase phosphorus availability	Vessey, (2003)
Mycorrhizae	Improve nutrient and water uptake	Smith & Read, (2008)
Decomposer fungi	Organic matter decomposition	Brady & Weil, (2017) ^[9]
Actinomycetes	Nutrient mineralization	Brady & Weil, (2017) ^[9]

10. Sustainable management and climate resilience

Sustainable management of entisols is essential for maintaining long-term agricultural productivity, environmental quality, and resilience against climate change (Lal, 2004) ^[38]. Because entisols are highly vulnerable to nutrient depletion, erosion, drought, and salinity, climate-resilient soil management practices are increasingly important for improving soil health and sustaining crop yields under changing environmental conditions (FAO, 2013). Sustainable management strategies focus on improving soil organic carbon, enhancing nutrient use efficiency, conserving soil moisture, and reducing land degradation. Carbon sequestration through incorporation of crop residues, compost, green manure, and conservation tillage plays an important role in improving soil quality and mitigating climate change (Lal, 2004) ^[38]. Increased soil organic carbon enhances aggregate stability, water-holding capacity, microbial activity, and nutrient retention in entisols. Conservation agriculture practices such as reduced tillage, residue retention, crop rotation, and cover cropping help minimize erosion and improve nutrient cycling (FAO, 2017). These practices also enhance resilience of crops against drought and temperature stress.

Climate-smart agriculture integrates sustainable soil management with efficient resource use and adaptation strategies (FAO, 2013). Efficient irrigation methods such as drip irrigation and sprinkler systems reduce nutrient leaching and improve water use efficiency in coarse-textured entisols. Integrated nutrient management involving organic manures, chemical fertilizers, and biofertilizers ensures balanced nutrient supply and minimizes environmental pollution (Fageria, 2012) ^[15]. Agroforestry systems additionally contribute to soil conservation, carbon storage, and biodiversity enhancement.

Long-term fertility restoration in entisols requires continuous monitoring of soil health and adoption of environmentally sustainable management practices (Srinivasarao *et al.*, 2014). Maintenance of vegetation cover, afforestation, residue recycling, and erosion control measures are important for preserving soil productivity. Therefore, sustainable and climate-resilient management practices are essential for enhancing the ecological stability and agricultural sustainability of entisols under future climate change scenarios.

Conclusion

Entisols are among the most fragile and weakly developed soil orders, characterized by poor structural development, low organic matter content, weak nutrient-retention capacity, and high susceptibility to erosion, nutrient leaching, and moisture stress. Although these soils support extensive agricultural activities in floodplains, coastal regions, and arid ecosystems, their long-term productivity is often constrained by nitrogen losses, phosphorus fixation, potassium depletion, sulfur deficiency, salinity, and micronutrient imbalances, particularly zinc and iron deficiencies. Nutrient dynamics in entisols are strongly influenced by soil texture, climate, parent material, pH, irrigation, and land management practices. Continuous cultivation, excessive tillage, residue removal, and indiscriminate fertilizer application further accelerate soil degradation and fertility decline. The review emphasizes that sustainable management of entisols requires integrated nutrient management approaches involving balanced

fertilization, organic amendments, crop residue recycling, conservation tillage, cover cropping, and precision nutrient management. Beneficial soil microorganisms such as rhizobacteria and mycorrhizae also play significant roles in nutrient cycling, nutrient solubilization, and improvement of soil biological activity. Climate-resilient strategies including carbon sequestration, conservation agriculture, efficient irrigation systems, and climate-smart farming practices are increasingly important for enhancing soil health and maintaining agricultural sustainability. Adoption of these integrated and eco-friendly management practices can substantially improve nutrient-use efficiency, crop productivity, environmental quality, and resilience of entisols under changing climatic conditions.

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