Eco. Env. & Cons. 28 (August Suppl. Issue) : 2022; pp. (S135-S146)
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ISSN 0971–765X

DOI No.: http://doi.org/10.53550/EEC.2022.v28i04s.020

Synergism of Beneficial Microbes Helps to Rejuvenate Flood and Landslide Affected Soils for Sustainable Agriculture – A Review

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(Received 12 November, 2021; Accepted 4 January, 2022)

ABSTRACT

Climatic disasters, like floods and landslides, are the major causes for the decline in soil fertility or soil organic matter. Soil organic matter influences the physical, chemical, and biological properties of soil; it is the fundamental aspect that discloses soil health. Microorganisms in the soil environment participate a critical task in the enhancement of soil nutrients and soil fertility. Even though microbial bioinoculants are widely studied for improving agriculture, the application of microbial consortium for the restoration of organic matter or soil fertility in the flood and landslide depleted soils are yet to be exploited. The part of living biomass, i.e. soil microorganisms in restoring soil organic matter seems to be crucial, as microbes are the major drivers in escalating organic matter in the soil. The living biomass recycles the nutrients in the soil by utilizing the plant and animal litter in the soil and offers the crops adequate nutrients. Thus, microorganisms can force the accumulation of stable and chemically diverse soil organic matter in poor fertile soils. Exploring such vibrant, complex advantageous interactions among microorganisms seems imperative to replenish organic matter exhausted soil. This article reviews the relevance of soil organic matter, the role of soil microorganisms in improving soil organic matter and emphasizes the need for intensive research in raising beneficial microbiome for replenishing soil organic matter and thus to rejuvenate the flood and landslide depleted soils to sustain agriculture.

Key words: *Soil organic matter, Synergism, Beneficial microbes, floods and landlsides.*

Introduction

Disasters in different modes impinge on multiple sectors in varying dimensions very rapidly. The Food and Agriculture Organisation in 2020 report about the global disaster rise by decade and claims more intense in the 2010s and strongly focus that the agriculture sector absorbs 25% of the total damage and loss from climate-related disasters. Extreme climate change can have a significant impact on crop quality and quantity by causing numerous ecological pressures, placing worldwide food security at danger (Shahzad *et al.*, 2021). Climate-resilient agricultural systems seem crucial to overcome its impact in the agricultural sector. Soil is an essential component of the environment and the terrestrial ecosystem's central organiser. For ideal soils suitable for agriculture, a balanced contribution of mineral components (sand: 0.05–2 mm, silt: 0.002–0.05 mm, clay: 0.002 mm), soil organic matter (SOM), air, and water is essential, as these components allow water retention and drainage, oxygen in the root zone,

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nutrients to facilitate crop growth, and physical hold up for plants (Parikh and James, 2012). Depending on the complex interactions between soil processes, factors and causes it is susceptible to degradation (Lal, 2015) which is a major concern that leads to poor productivity as soil degradation implies a decline in soil quality (Lal, 2009). Soil organic matter (SOM) content, which responds efficiently to changes in soil management, tillage, and plant production, is the fundamental foundation (Baker *et al.,* 2007).

It is critical to restore soil organic matter and nutrients so as to preserve soil fertility and balance in the agro-ecosystem. Land degradation, decreased soil fertility, and rapidly declining production levels are all difficulties that most parts of the world face. Maintaining soil quality by increasing organic matter content can help to alleviate these issues. In most developing nations, nutrient depletion and soil fertility loss are key reasons of low production (Berner *et al.,* 2016; Gaskin, 2020). SOM is a complex mixture of soil microbial and insect corpses, plant detritus, animal manures, dead roots, and humus in various states of decomposition and reformation that makes up the organic part of soil. The soil organic carbon pool should be raised above the critical value (10 – 15 g/kg) to reach the restorative soil stage.

Soil organic matter is used as food by soil organisms, including microorganisms. Organic matter in the soil and soil organisms are intricately linked. Microorganisms are the catalysts for most nutrient-releasing activities, utilising SOM as food, and therefore making soils productive (Bot and Benites, 2005; Gaskin, 2020; Ingham, 2000). Diverse microorganisms can be found in the environment which collaborate and make compatible interactions among themselves that may be a short term interaction or long term. There are study reports which explain the relevance of the rhizosphere microbiome and their link to plant nutrition (Jacoby *et al.,* 2017), their applications to overcome the gradual depletion of soil fertility and the activities of soil enzymes (Jabborova *et al.,* 2020). Microorganisms not only decompose the organic materials introduced to the soil, but they also have a major job in the production of a complex mixture of organic molecules known as soil organic matter (SOM) (Rao *et al.,* 2019).

Climate change is a current agricultural issue, because without a healthy microbial population, nutrients are no longer recycled, opportunistic pests can invade, and farmers are dependent on chemicals to replace organic soil activities (Wallenstein, 2017). Feeding microbes (e.g., feeding the soil with useful microorganisms that can effectively boost organic matter) can restore degraded soil to a healthy and productive platform. This article reviews the different aspects of soil-soil organic-microbial interaction that provides information to stimulate a new reflection on a lasting relationship with the soil. It also reveals the benefits of soil organic matter and combined efforts of valuable microorganisms in raising infertile soil to fertile one and to sustain agriculture.

Impact of flood and landslides on agricultural soils

Climate change is a significant issue of the contemporary environmental discourse. The most prevalent natural disasters that influence human society and the economy are extreme precipitation events, landslides, and floods (Coumou and Rahmstorf, 2012; Crozier, 2010; Roxy *et al.,* 2017). Flood and landslides also modify the landscape. Landslides are under the pressure of gravity. Landslides are defined as the downward movement of a mass of rock, earth, or debris under the effect of gravity Cruden (1991). Floods occur worldwide and are caused by the frequent occurrence of extreme precipitation events (Fowler *et al.,* 2010), which often happens after heavy rains. This sudden movement of materials agitates the soil's properties in all aspects. Furthermore, Dottori *et al.* (2018) observed that future flood damages are anticipated to be unevenly distributed around the globe, with Asia bearing the brunt of the losses.

The soil nutrients dissolved in floodwaters are transported from plain surfaces to rivers and make soil richer, fertile and productive and the same also gets reversed back from the soil to rivers (Gallardo, 2003). As a result, flooding can cause both an increase and a loss in the nutritional content of the soil. Research reports on the soil nutritional status in the flood-affected soils show these variations. Flood helps positively to soil qualities by supplying nutrients that may be deficient in the soil, according to Stephen (1993). After flooding, total porosity, moisture content, pH, and organic carbon in soil were all higher than before flooding (Njoku and Okoro, 2015). Flood has modified the nutrient status within soils before and after floods, according to the Indian Department of Soil Survey and Soil Conservation (Report No: 1455, 2018), where lack of major and minor nutrients has been detected in many areas. To presume from these contradictory reports, the landscape plays a key role, hence, sediments and deposits result in nutrient rise whereas, long period waterlogging results in the depletion of nutrients. However, depending on the nature of nutrients, the augment and decline may differ. For example, organic matter, nitrogen, phosphorus, sulphur, iron, manganese, copper, and zinc were much greater in sediments deposited in agricultural regions following flooding. However, after the Kerala state flood in 2018, topsoils were considerably lower in potassium, calcium, magnesium, and boron.

The Department of Soil Survey and Soil Conservation conducted a report on the soil flood status in Kerala (Report No: 1455, 2018) in a post-flood scenario in thirteen districts of Kerala to assess the impact of flood and landslides on soil quality, concluding that flood has deteriorated soil quality by impairing its physical and chemical properties. Soil compaction, soil crusting, loss of aggregate stability have negative impact on the microbes and microflora in the soil. Poor organic matter was seen in soils. Deficiency in potassium, calcium, magnesium and boron is widely noticed apart from localized deficiencies of zinc and phosphorous. Researchers discovered a 21% drop in aggregate stability in cultivated soils after 14 days of flooding, which they believe is irreversible (De-Campos *et al.,* 2009). The report specifically mentions the importance of the native microbial floral change and fortification using microbial inoculants to improve microbial status is quite useful and thus improves the nutrient availability to crops.

Both the calamities, mudflow or debris expose the subsurface horizon and the topsoils are removed. Hence, both flood and landslides are always a drop to agricultural output as topsoil is disturbed or lost, which is the part of the soil horizon and generally with better structure with a elevated level of organic matter and nutrients (USDA, 2018). Lal and Stewart (1990) opines that the left behind soil after floods and landslides is 1.3 to 5 times less in organic matter than the soil removed and cease to be suitable for crop cultivation. These soils are very hard to re-vegetate as flooding create anaerobic condition and washes out natural soil microorganisms which may impact on the soil organic matter and nutrient availability as they have strong roles in various nutrient cycles. Microbial processes use organic materials as an energy source (electron donor) (Stevenson, 1986) and the store and supplier of plant nutrients, the reduction is disadvantageous for agricultural soils and important in maintaining soil fertility.

Berner *et al.* (2016) reviewed that exhausted and damaged soils cannot offer the desired performance in organic farming. Soil biota performs the most significant part in nutrient cycle activities by breaking down carbon structures and rebuilding new ones or storing carbon in their biomass, and thus enhances a soil's ability to give sufficient nutrients to a crop for a healthy harvest (Bot and Benites, 2005). Excess nutrients (N, P, and S) are released into the soil in plant-useable forms when they break down organic materials. Organic matter breakdown is mostly a biological process that occurs naturally. Three key elements influence its speed: soil organisms, the physical environment, and the quality of organic materials (Brussaard, 1994). Various components are emitted during the breakdown process, including carbon dioxide (CO2), energy, water, and others. A more complex organic matter known as humus is created after the breakdown of dead materials and altered organic matter (Juma, 1998). Humus has an impact on soil properties and decomposes slowly, darkening the soil, increasing soil aggregation and aggregate stability, increasing the CEC (ability to attract and retain nutrients), and contributing N, P, and other nutrients. The presence of organic matter, particularly more stable humus, increases the potential to hold water and sequester carbon from the atmosphere (Bot and Benites, 2005). Concerns about soil degradation, soil fertility decline, global warming and induced CO2 emissions, among other things, have prompted much research into SOM, resulting in a better understanding of its structure and activities. However, extensive research aimed at

Landslide at Munnar

Fig. 1. Report by the Department of Soil Survey and Soil Conservation, Kerala, India, 2018

enhancing and restoring SOM in disturbed and undisturbed soils remains inhibited. Rao *et al.* (2019), Berner *et al.* (2016) and Lal (2015) suggested that conserving fertile soils is very important, but has not received enough attention.

Soil components relevant for the restoration of agricultural productivity

Soil fertility is a crucial aspect of farming as productivity depends mostly on it. Soil health depends upon the sources of available nutrients, agricultural methods adopted, climatic conditions, etc. which can be analyzed through various soil health indicators like texture, aggregate stability, water mobility, etc. Soil fertility can also be defined in terms of the soil's ability to increase plant productivity while staying within budget restrictions (Campbell, 1998). The three major solid components of soil are minerals, organic components, and microbes. They have a significant impact on terrestrial systems' physical, chemical, and biological properties and processes (Mohammadi *et al.*, 2001).

Soil degradation is a key stumbling block to increasing agricultural output to the levels required. The parent material, climate, time, organisms and topography influence the distribution of soil components (Jenny, 1941) and all these have a role in confirming the suitability of a soil for agriculture (Parikh and James, 2012). The United States Department of Agriculture (USDA, 2018) suggested a number of predefined indicators to evaluate soil health, which was chosen through a multi-organizational collaborative effort. Six major soil physical and biological processes that must work effectively in a healthy soil have been identified: General microbial activity: carbon food source, bioavailable N, and microbial community diversity; organic matter dynamics and carbon sequestration; soil structural stability (infiltration); general microbial activity: carbon food source, bioavailable N, and microbial community diversity. Many of the factors in the soil health indicators are well associated to each other, according to Aparna *et al.* (2014, 2016) and Malhotra *et al.* (2015). They also claimed that the activity of soil enzymes are frequently connected.

Organic matter content in surface soils ranges from 1 to 6%, with SOM decreasing as depth increases (Brady and Weil, 2007). The quantity and quality of soil organic carbon define the component of soil (Krupenikov *et al.*, 2011; Manlay *et al.*, 2007) and is the most accurate way to track soil degradation, particularly that induced by rapid erosion (Rajan *et al.*, 2010). Globally, the depletion of the SOC pool is the leading driver of soil degradation (Diacono and Montemurro, 2010), and plant-available N and other critical nutrients like P and S are also depleted. Developing measures to ensure that the SOC pool rises over the threshold or crucial level of 10 to 15 g/kg (1.0 percent –1.5 percent), which is critical for minimising soil degradation risks and reversing trends (Lal, 2015). Restoring the quality of degraded soils is a difficult task since re-carbonization of the depleted SOC pool necessitates frequent inputs of biomass-C and critical elements (i.e., N, P, and S), all of which are necessary for a variety of functions (Lal, 2014). Soil organic - C has a strong association with biological quality indicators such as microbial biomass and soil enzymes (Bhaduri and Purakayastha, 2014; Sarkar *et al.*, 2009).

The primary macronutrients are needed in greatest quantities than the secondary macronutrients and the micronutrients or trace nutrients are required in minute quantities (Parikh and James, 2012). The relevant soil characteristics and nutritional elements of soils and their critical limits are tabulated in Table 1. The critical limits of the nutrients are vital, as, if in excess, can cause negative impacts. The addition of nutrients to promote fertility can boost agricultural yields, but it's important to evaluate the impact on the soil. Artificial fertilizers are more convenient to use and handle than animal manures and organic fertilizers, yet they can cause serious soil issues. Organic fertilizers provide the added benefit of enhancing soil structure and encouraging the growth of beneficial soil organisms. As a result, they're a good choice for proponents of sustainable agriculture (Mason, 2003).

Living creatures, carbonaceous remains of organisms in the soil, and organic chemicals formed by current and previous metabolism in the soil are all part of the organic matter in the soil (Brady and Weil, 1999). The soil biota plays a vital role in reducing the risk of degradation and is a chief component of global terrestrial biodiversity with key ecosystem functions. Focusing on microbial activity is crucial to restore and improve soil quality. Managing the soil microbial quality by either a microbiological quality index (Moreno *et al.*, 2008) or a microbiological degradation index (Bastida *et al.*, 2006) can help for a decision. Microbial enzymatic activities such as dehydrogenases and other hydrolases in the soil are relevant in such restorative practices (Bastida *et al.*,

Table 1. Essential plant Nutrients with critical limits

Essential Plant Element	Critical Limits		
	Low	**Medium**	**High**
Electrical conductivity	<1mmhos/cm	1-4 mmhos/cm	>4mmhos/cm
CEC	<5 cmol/kg	5-16cmol/kg	>16cmol/kg
Organic Carbon %	<0.76%	0.76-1.5%	>1.5%
Available Nitrogen	<280kg/h	280-450kg/h	> 450 kg/ h
Available Phosphorous	<10 kg ha-1	10-24 kg ha^{-1}	>24 kg ha-1
Available Potassium	<115 kg ha-1	115-275 kg ha-1	>275 kg ha-1
Available Sulphur	<5 mg kg-1	5-10 mg kg-1	>10 mg kg-1
Water holding capacity	<30%	30-50%	>50%
	Deficient	**Adequate**	
Available Boron	< 0.5ppm	>0.5 ppm	
Available Copper	< 0.12 ppm	> 0.12 ppm	
Available Iron	< 5ppm	>5.0 ppm	
Available Manganese	< 1.0ppm	>1 ppm	
Available Zinc	< 0.60 ppm	> 0.60 ppm	

2006). The number of general microorganisms of soils amended with the organic matter was revealed by Nishio and Kusano (1980). The abundance and activity of Actinobacteria are intimately related to the biological health of the soil (Aparna *et al.,* 2014). When the biomass of bacteria and fungi, as well as enzyme activities, were compared to soil organic matter (Mohammadi *et al.,* 2001) and biochemical properties (Lynch, 1983), it was discovered that microbial communities provide essential ecosystem services such as nutrient cycling, pathogen suppression, soil aggregate stabilisation, and xenobiotic degradation. Agricultural management approaches have been demonstrated to affect microbial biomass, activity, and community structure in the soil.

The relevance of microbial population in the regeneration of soil organic matter and other essential nutrients is evident with research proofs, but still, the focused research works for such restorative works by improving the soil organic carbon and the availability of macro and micronutrients is still negligible. According to Lal (2015) soil resources must be used, improved and restored. Hence, restoration of soil quality seems societal essentiality and necessitates a coordinated approach**.**

Benefits of soil organic matter to soil characteristics

The single most important indication of soil fertility and productivity is organic matter, according to most experts (Rowell, 1994). It is a highly important soil component made up mostly of dead or decomposing plant and animal leftovers. Soil organic matter provides soil the deep black colors and rich aromas (Parikh and James, 2012), is a fundamental component of comprehensive soil fertility management and plays a critical role in soil processes (Brady and Weil, 2007). According to Baldock and Nelson (2000), Mohammadi *et al.* (2001) and Wilkinson (2000) the biological, physical and chemical aspects of the soil are influenced by its organic matter content. They also suggest that organic matter can also exert a significant influence on the ecosystem's functioning and processes. According to Ashman and Puri (2002), Mikkuta *et al.* (2007), and Parikh and James (2012), the benefits of organic matter in the soil include holding and supplying available plant nutrients (N, P, and S), augmenting the soil's cation exchange capacity, beneficially influencing soil structure, pH buffering capacity, and acting as food for soil organisms ranging from bacteria to worms, which are important elements in the nutrient and carbon cycles.

Organic matter, which tends to deposit as a coating on the surfaces of crumbs, contributes to the binding property. Organic matter is a key factor in soils that holds mineral particles together (Oades, 1993). Miniature microaggregates (53 pm) around a particulate organic core, materials that have been physiologically bundled and held together by humified organic matter form larger microaggregates and smaller macroaggregates (2,000 pm) (Beare *et al.,* 1994; Golchin *et al.*, 1994). Roots, fungal hyphae, and bigger fragments of plant residues, which interconnect soil aggregates by bonding, penetration, and/or physical enmeshment, stabilise macroaggregates > 2,000 pm (Churchman and Foster, 1994; Foster, 1994). The crumbs are covered in organic material, which shields them from excess moisture. In this manner, there are less instances of crumbs bursting in the rain, and there is less capping/siltation of the soil. Crumbs of heavier soils do not hold together as much on areas rich in organic matter. Soil can be cultivated at a wider range of humidity levels. With clay-humus complexes, organic matter not only helps lighten heavy soils but also strengthens the cohesiveness of light soils (Berner *et al.,* 2016). Cultivated soils with good organic matter are less subject to wind and water erosion. The presence of litter layers or organic horizons (dark color soil) can insulate the soil against fluctuations in air temperature and solar heating (Baldock and Nelson, 2000).

Organic materials can have a direct and indirect impact on soil water retention. SOM has the ability to absorb and store large amounts of water, up to twenty times its own mass (Stevenson, 1994). Organic matter in the form of surface residues can also have a direct impact on water retention by lowering evaporation and enhancing water infiltration. Organic matter, particularly organic carbon-rich soil, has a huge water-holding capacity, thus it can hold a lot of water and help retain it in the soil (Rawls *et al.,* 2003).

Cation Exchange Capacity is also supplied by organic substances (CEC). CEC is mostly derived from clay and organic materials (Peinemann *et al.,* 2000). Organic matter contributes nearly all of the cation exchange capacity (CEC) of peats, forest litter, and humus layers, as well as the CEC of surface layers of mineral soils (Stevenson, 1994).

Furthermore, organic matter has an impact on and modifies several soil properties. Wilkinson (2000) and Mohammadi *et al.* (2001) illustrate the importance of organic matter content in the soil property. Soil structural stability is most closely associated with total soil organic matter concentration. Soil organic matter accumulated is due to the biological contributions, water content, and temperature, which regulates decomposition and also the soil texture. The major input is from plants, the primary producers by seasonal shedding of leaves and roots and the whole plant on death. In addition, the humus component of SOM enhances soil structure by enhancing soil water-holding capacity, infiltration, and aeration, which results in enhanced shoot, root length (Chen and Aviad , 1990), and enhanced enzyme activity (Vaughan and Malcolm, 1985).

It is clear that organic matter provides nutrients and environment to living organisms in the soil, organic matter also attach soils particles into aggregates thus promotes granulation, improve aeration, improve soil structure, retain moisture, protect against abrupt temperature or chemical changes, encourage the activity of beneficial soil organisms, protect from the effect of rainfall and minimize erosion.

Relevance of microorganisms in restoring SOM / soil health

Soil fertility decline happens over evolutions due to natural calamities like flood and soil erosion, human invasion, and tillage (Berner *et al.,* 2016; Karmakar *et al.,* 2016; Mohammadi *et al.,* 2001). The soil microbiome is one of the most sensitive indicators of soil health because it signals the direction and severity of changes in ecosystem structure and function far earlier and better than other markers. The transformation of soil organic matter, nutrients, and most critical soil activities is mediated by soil microbes. Microbes were once assumed to be limited to decaying plant and animal waste; however, their function in the resynthesis of organic matter was later discovered.

On a microbiological level, fertility refers to a microbial population that releases nutrients quickly enough to support rapid plant growth while simultaneously contributing to soil aggregate production (Rashid *et al.,* 2016). Microbes play the most critical function in SOM synthesis, according to Waksman (1936). Different microbial populations promote the buildup of chemically varied and stable SOM produced by soil bacteria (Rao *et al.,* 2019). Because microbial-derived carbon compounds are the key elements of stable, long-term organic matter repositories (Grandy and Neff, 2008), the most widely recognised mechanism of SOM production is that soil microorganisms are the primary agents of SOM creation (Cotrufo *et al.,* 2013; Miltner *et al.,* 2012; Schmidt *et al.,* 2011). Carbon from plants serves as the primary substrate for microbial development and turnover, and so serves as a precursor to the production of stable SOM (Bradford *et al.,* 2013). Ex vivo modification and in vivo turnover are two mechanisms proposed by Liang *et al.* (2017) to explain soil C dynamics driven by microbial catabolism and/or anabolism, as well as the quantity of organic C in soils and microbial involvement. They introduced the'soil microbial carbon pump' (MCP) as a conceptual framework for demonstrating how microorganisms play a role in soil C storage. All of the additional organic components are totally broken down by bacteria and re-metabolized by them. SOM should be considered a synonym for all kinds of microbial biomass in soil, according to Rao *et al.* (2019).

Microbial residues and necromass (dead biomass) have been discovered as a substantial source of SOM (Frey *et al.,* 1999), accounting for 5 to 50% of total SOM. Using HR-MAS NMR, Spence *et al.* (2011) discovered that microbial products account for 50% of SOM. Bacteria and fungal cell envelopes are maintained in soil and contribute significantly to the development of tiny particulate SOM (Miltner *et al.,* 2012). 50% of the carbon produced from microbial biomass stayed in the soil. Microbial metabolism can cause chemical variability in SOM. Microbial by-products, according to Kallenbach *et al.* (2016), are also key drivers of SOM chemical variability. They further believe that due to significant physicochemical interactions within the soil matrix, microbial necromass appears to persist longer than lignin-rich materials. Despite increased extracellular enzyme activity, more plant C being diverted into microbial biomass may eventually result in higher stable soil C deposition over time (Cotrufo *et al.,* 2013). The functions of specific microbes in metabolism of plant components and thus in restoring agriculture are identified. Febria *et al.* (2020) recognized that microbes in sediments could transform organic matter to electrons. Acidobacteria have designated important ecological roles in diverse metabolic pathways, decomposition of biopolymers exopolysaccharide secretion, plant growth promotion and regulation of biogeochemical cycles (Kalam *et al.,* 2020). The microbial interactions between them and with the soil rhizosphere have crucial functions in the restoration of agricultural soils affected by natural calamities.

Microbial Interactions in restoring the soil organic matter/soil fertility

The significance of microorganisms in the biological fertility of the soil is evident. Their interaction with other soil components depends upon varying conditions. Johns (2017) opined that these complex and dynamic interactions of soil microorganisms are the least understood fertility component, and exploring such interactions and comparing with the influencing factors is most vital if agricultural production is to meet the requirements of the growing population. He also suggested that fertile soils always teem with microorganisms.

Healthy soils will contain microbiomes that help to avoid disease, improve nutrient cycling and to reduce plant stress by swiftly and efficiently converting dead plant components into soil organic matter. Profitable and effective farming is possible in healthy soils, with minimum inputs. The relevance of feed microorganisms to create new soils was also explained by Wallenstein (2017). He described microbial complex interactions, in which soil microorganisms work together in teams to execute biochemical activities like converting nitrogen from an inert gas to plant-usable forms and recycling it back into dissolved forms from dead plant components.

Co-metabolism is a illustrious system of valuable interaction between microorganisms of different types. There are complex resources in soils which the microorganisms are unable to catabolize alone, and hence many microorganisms assist as a consortium to produce all the enzymes essential for the catabolic pathway and are called co-metabolism (Bouchez *et al.,* 1999). According to Loccos *et al.* (2014), such a consortium contains strains that degrade metabolic intermediates to correct for inhibition, as well as when a strain's product is used as a substrate by other strains. Haseena *et al.* (2016) have used a consortium of thermophilic microorganisms for aerobic composting and increased efficiency of composting different raw materials. Employing such consortium as feed microbes into the soil for sustaining agriculture in flood and landslide depleted soils may bring out better yield in quantity and quality.

Plant and animal matter can be broken down into its fundamental components by millions of microbial species in the soil (bacteria and fungi). Bacteria and fungi are involved in practically all soil mineralization processes. Minerals and organic matter are closely associated with microorganisms in the soil environment, and they are also closely associated with each other. These components' interactions have a huge impact on terrestrial processes that are crucial to environmental quality and ecosystem health (Mohammadi *et al.,* 2001).

A crop-based integrated nutrient management plan for degraded soils could make use of organic additions with bacteria and fungus consortiums and other techniques (Medina *et al.,* 2010; Chaer *et al.,* 2011). These inoculations can be used to exploit, translocate, mineralize, and mobilise soil P, K, and Fe reserves, as well as enhance organic matter and fix nitrogen from the atmosphere. (Figueiredo *et al.,* 2011; Ahemad and Kibret, 2014; Leifheit *et al.,* 2014; Nguyen and Bruns, 2015; Owen *et al.,* 2015). Rao *et al.* (2019) used a mixed microbial consortium comprising Arthrobacter, Streptomyces, and Lysinibacillus to boost soil biological activity, carbon mineralization, and soil organic matter synthesis. Bacillus subtilis and Azospirillum brasilense could improve wheat growth, morphological and physiological characteristics, osmolytes production, and antioxidant enzymes by conferring drought tolerance and increasing antioxidant enzymes (Ilyas et al., 2020). Mycorrhizae (root fungi) create a symbiotic relationship with plants, infecting the root and allowing the latter to grow in a larger region of soil (Surendra, 2010). Mycorrhizal fungi add to the soil structure's beneficial characteristics. They allow substances to be exchanged between plants that are attached to them (Berner *et al.,* 2016), have symbiotic associations with the majority of the crops and are even used as biocontrol agents to control wilt in tomatoes (Surendra, 2010). PGPR can be used to manage plant disease in an environmentally responsible manner while also promoting plant growth and crop yield (Shaikh *et al.,* 2016). Rice plant yield efficiency was improved with three PGPR consortia and selected a best one (Kalani *et al.,* 2021).

The microbial interactions also benefit the soil by confiscating the floods and landslide-borne contaminations. The efficient function of microbial inoculants (bio-inoculant) in bioremediation is one of the latest known outputs from soil research. Bioremediation using potential microbes to clean up contaminated environments is a promising technology (Kour *et al.,* 2021). Sayyed *et al.* (2015) identified an *Enterobacter* isolate with high binding affinity and root colonization capability as an efficient bio-inoculant in the bioremediation in heavy metal contaminated soil. Co-inoculation of bacteria and fungi, with or without organic fertilizer, is more effective than a single inoculum in restoring soil fertility and organic matter content. (Rashid *et al.,* 2016). To explore these results and to utilize it for the rejuvenation of the depleted agricultural soils due to floods and landslides, the current microbial status and the nutrient analysis of the disturbed agricultural soils has to be examined to identify potential multifunctional consortium of microorganisms. The efficiency of these isolates has to tested on pot cultures and field which confirms their efficiency to restore the soil organic matter or soil fertility to sustain agriculture in flood and landlside depleted agriculture plots.

Social impact and relevance of synergistic microbes in the present scenario

The expected growth in world population between 8 and 10 billion people in the next 50 years (Bongaarts, 2009; Lutz, 2001) demands an enhance in provisions (Alexandratos, 1999; Tilman *et al.*, 2002), therefore mitigating soil degradation must be prioritised in global society (Parikh and James, 2012). Soil organic matter accounts for a significant component of the terrestrial biosphere's organic carbon. The buildup of organic matter is helpful to agricultural soil functions. In contrast, management techniques and natural disasters that cause a decrease in soil organic matter content emit CO2, a major greenhouse gas, in addition to having a negative influence on agricultural productivity and soil resilience in general (Lal, 1998).

Soil organic matter, like soil microbial biomass, soil biological activity, and all other soil health indices, is highly connected. SOM and soil microbial biomass are thus two sides of the same coin that form a

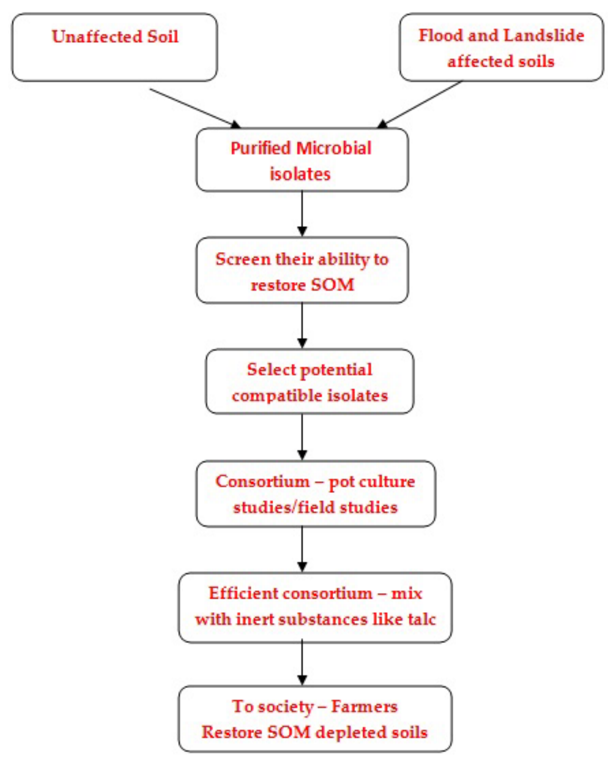

Fig. 2. Illustrating the steps for restoring SOM in flood and landslide depleted soils

continuum. Farmers and producers can retain atmospheric carbon while improving soil quality and possibly lowering input costs by adding SOM conservation into management strategies (McCauley, 2017). A comparative investigation on less productive and productive agricultural fields, which can develop a hand full of productive microbial consortiums may bring back the soil fertility, can benefit agriculture, farmers, and society and thus sustain agriculture by protecting the precious and essential pillar "SOM/Soil fertility". The steps for restoration of depleted SOM in soils are depicted in Figure 2.

Conclusions

The blow of flood and landslides in the agricultural soils affect the yield of the crop in the later years as flood deteriorated the soil quality by weakening its physical, chemical and biological elements. The soil organic matter remained a major loss in the soil along with nutritional deficiencies, soil acidity, soil compaction, loss of aggregate stability, structural variation, etc. Analyzing the soils will show the current state of native microorganisms that have been harmed by flooding, as well as appropriate remedial treatments; supplementation of organic manures with biofertilizers and microbial inoculants is particularly effective in reviving the soil's microbial status. This will boost microbial activity in the soil and increase crop nutrient availability.

Acknowledgements

The post doctoral fellowship provided to the first author by the Kerala State Council for Science, Technology and Environment (KSCSTE) Back To Lab Programme is greatly acknowledged.

Conflicts of Interest

The authors declare that there is no competing interest

References

Ahemad, M. and Kibret, M. 2014. Mechanisms and applications of plant growth-promoting rhizobacteria: Current perspective. *J. King Saud Univ. Sci*. 26(1): 1-20.

Alexandratos, N. 1999. World food and agriculture: Outlook for the medium and longer-term. *Proc. Natl. Acad. Sci. U.S.A.* 96(11): 5908-5914.

Aparna, K., Pasha, M.A., Rao, D.L.N. and Krishnaraj, P.U. 2014. Organic amendments as ecosystem engineers: microbial, biochemical and genomic evidence of soil health improvement in a tropical arid zone field site. *Ecol. Eng*. 71: 268-277.

Aparna, K., Rao, D.L.N. and Balachandar, D. 2016. Microbial populations, activity and gene abundance in tropical Vertisols under intensive chemical farming. *Pedosphere*. 26(5): 725–732.

Ashman, M.R. and Puri, G. 2002. *Essential soil science: a clear and concise introduction to soil science*. Blackwell Science Ltd, Oxford.

Baker, C.J.; Saxton, K.E.; Ritchie, W.R.; Chamen, W.C.T.; Reicosky, D.C.; Ribeiro, F.; Justice, S.E.; Hobbs, P.R. 2007. *No-tillage Seeding in Conservation Agriculture*. 2nd edition. Food and Agriculture Organization of the United Nations, United Nations.

Baldock, J.A. and Nelson, P.N. 2000. *Soil Organic Matter*. Handbook of Soil Science, Sumner M.E, CRC Press, BocaRaton, USA.

Bastida, F., Moreno, J., Hernandez, T. and Garcia, C. 2006. Microbiological degradation index of soils in a semi-arid climate. *Soil Biol. Biochem.* 38(12): 3463–3473.

Beare, M.H., Cabena, M.L., Hendrix, P.F. and Coleman, D.C. 1994. Aggregate-protected and unprotected organic matter pools in conventional and no-tillage soils. *Soil Sci. Soc. Am. J.* 58(3), 787-795.

Berner, A., Böhm, H., Brandhuber, R., Braun, J., Brede, U., Roesgen, J.C., Demmel, M., Dierauer, H., Doppler, G., Ewald, B., Fisel, T., Fließbach, A., Fuchs, J., Gantlett, R., Gattinger, A., Häberli, H., Heß, J., Hülsbergen, K.J., Köchli, M., Kolbe, H., Koller, M., Mäder, P., Müller, A., Neessen, P., Patzel, N., Pfiffner, L., Schmidt, H., Weller, S., Tolhurst, I. and Wild, M. 2016. *The Basics of Soil Fertility. Basic guide.* Research Institute of Organic Agriculture (FiBL) and The Organic Research Centre, Elm Farm, CH-5070 Frick and UK.

Bhaduri, D. and Purakayastha, T.J. 2014. Long-term tillage, water and nutrient management in rice-wheat cropping system: Assessment and response of soil quality. *Soil Till. Res.* 144(1): 83-95.

Bongaarts, J. 2009. Human population growth and the demographic transition. *Philos.Trans. R. Soc. Lond. B-Biol. Sci.* 364(1532): 2985-2990.

Bot, A. and Benites, J. 2005. *The importance of soil organic matter*. Food Agriculture Organization. Rome.

Bouchez, M., Blanchet, D., Bardin, V., Haeseler, F. and Vandecasteele, J.P. 1999. Efficiency of defined strains and soil consortia in the biodegradation of polycyclic aromatic hydrocarbon (PAH) mixtures. *Biodegradation*. 10(6): 429–435.

Bradford, M.A., Keiser, A.D., Davies, C.A., Mersmann, C.A. and Strickland, M.S. 2013. Empirical evidence that soil carbon formation from plant inputs is positively related to microbial growth. *Biogeochemistry.*

113(1-3): 271-281.

Brady, N.C. and Weil, R.R. 1999. *The Nature and Properties of Soils*. 12th edition. Prentice-Hall, Inc, Upper Saddle River, New Jersey.

Brady, N.C. and Weil, R.R. 2007. *The Nature and Properties of Soils.* 14th edition. Prentice Hall, Inc, Upper Saddle River, New Jersey.

Brussaard, L. 1994. *The ecology of soil organisms in sustainable farming systems. Soil biota management in sustainable farming systems,* Pankhrust C. *CSIRO, Australia*.

Campbell, L.C. 1998. Managing Soil Fertility Decline. *J. Crop Prod.* 1(2): 29-52.

Chaer, G.M., Resende, A.S., Campello, E.F.C., de, F., aria, S.M. and Boddey, R.M. 2011. Nitrogen-fixing legume tree species for the reclamation of severely degraded lands in Brazil. *Tree Physiol.* 31(2): 139-149.

Chen, Y. and Aviad, T. 1990. Effects of humic substances on plant growth, p. 161-186. In: McCarthy, P., Clapp, C.E., Malcolm, R.L. and Bloom, P.R. (Edited) *Humic Substances in Soil and Crop Sciences: Selected Readings*; Soil Science Society of America, Madison, WI.

Churchman, G.J. and Foster, R.C. 1994. *The role of clay minerals in the maintenance of soil structure*. Trans. l5th World Congress of soil science, International Soil Science Society. Acapulco, Mexico.

Cotrufo, M.F., Wallenstein, M.D., Boot, C.M., Denef, K. and Paul, E. 2013. The Microbial Efficiency Matrix Stabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: do labile plant inputs form stable soil organic matter. *Glob. Change Bio.*19: 988-995.

Coumou, D. and Rahmstorf, S.A. 2012. Decade of weather extremes. *Nat. Clim. Chang.* 2: 491–496.

Crozier, M.J. 2010. Deciphering the effect of climate change on landslide activity: A review. *Geomorphology.* 124(3-4): 260-267.

Cruden, D.M. 1991. A Simple Definition of a Landslide. Bulletin of the International Association of Engineering. *Geology*. 43: 27-29.

De-Campos, A.B., Mamedov, A.I. and Huang, C. 2009. Short-Term Reducing Conditions Decrease Soil Aggregation. *Soil Sci. Soc. Am. J*. 73: 550-559.

Diacono, M. and Montemurro, F. 2010. Long-term effects of organic amendments on soil fertility: A review. *Agron. Sustain. Dev.* 30: 401–422.

Dottori, F., Szewczyk, W., Ciscar, J.C., Zhao, F., Alfieri, L., Hirabayashi, Y., Bianchi, A., Mongelli, I., Frieler, K., Betts, R.A. and Feyen, L. 2018. Increased human and economic losses from river flooding with anthropogenic warming. *Nat. Clim.* 8: 781-786.

Febria, F.A., Jonesti, W.P. and Zakaria, I.J. 2020. Energy harvesting with estuarine sediment microbial fuel cell. *Asian Jr. of Microbiol. Biotech. Env. Sc.* 22(1): 189-193.

Figueiredo, M.V.B., Seldin, L., de Araujo, F.F. and Mariano, R.L.R. 2011. Plant growth-promoting rhizobacteria: fundamentals and applications. p. 21-43. In Maheshwari, D.K. (Edited) *Plant Growth and Health Promoting Bacteria.* Springer, Berlin Heidelberg.

Foster, R.C. 1994. Microorganisms and soil aggregates. p. 144-155. In: Pankurst, C.E., Doube, B.M., Cupta, V.V.S.R. and Grace, P.R. (Edited) *Soil Biota: Management in Sustainable Farming Systems.* CSIRO, East Melbourne, Australia.

Fowler, H.J., Cooley, D., Sain, S. R. and Thurston, M. 2010. Detecting change in UK extreme precipitation using results from the climateprediction.net BBC climate change experiment. *Extremes*. 13(2): 241–267.

Frey, S.D., Elliott, E. and Paustian, K. 1999. Bacterial and fungal abundance and biomass in conventional and no-tillage agroecosystems along two climatic gradients. *Soil Biol. Biochem.*. 31(4): 573-585.

Gallardo, A. 2003. Spatial variability of soil properties in a floodplain forest in Northwest Spain. *Ecosystems*. 6(6): 564–576.

Gaskin, J. 2020. *Benefits of increasing soil organic matter.* Chapter 3 In: Conservation Tillage systems in the south East: Production, Profitability and stewardship, Sustainable Agriculture Research and Education (SARE) program, University of Georgia Francisco Arriaga, University of Wisconsin–Madison Alan Franzluebbers, USDA-ARS Yucheng Feng, Auburn University**.**

Golchin, A., Oades, J.M., Skjemstad, J.O. and Clarke, P. 1994. Soil structure and carbon cycling. *Aust. J. Soil Res*. 32(5): 1043-l068.

Grandy, A.S. and Neff, J.C. 2008. Molecular C dynamics downstream: the biochemical composition sequence and its impact on soil organic matter structure and function. *Sci. Total Environ.* 404: 297–307.

Haseena, A., Nishad, V.M. and Balasundaran, M. A. 2016. Consortium of thermophilic microorganisms for aerobic composting. *IOSR J. Environ. Sci. Toxicol. Food Technol.* 10(1): 49-56.

Ilyas, N., Mumtaz, K., Akhtar, N., Yasmin, H., Sayyed, R.Z., Khan, W., Enshasy, H.A.E., Dailin, D.J, Elsayed, E.A. and Ali, Z. 2020. Exopolysaccharides Producing Bacteria for the Amelioration of Drought Stress in Wheat. *Sustainability*. *12(21):* 8876.

Ingham, E.R., Moldenke, A.R. and Edwards, C.A. 2000. The soil food web. In: Tugel, A.J., Lewandowski, A.M. and Deb Happe-vonArb, D. (Edited) *Soil biology primer*. Rev. edition, Soil and Water Conservation Society, Ankeny, USA.

Jabborova, D., Wirth, S., Kannepalli, A., Narimanov, A., Desouky, S., Davranov, K., Sayyed, R.Z., El Enshasy, H., Malek, R.A., Syed, A. and Bahkali, A.H. 2020. Co-Inoculation of Rhizobacteria and Biochar Application Improves Growth and Nutrients in Soybean and Enriches Soil Nutrients and Enzymes. *Agronomy. 10*(8): 11-42.

Jacoby, R., Peukert, M., Succurro, A., Koprovova, A. and Kopriva, S. 2017. The role of soil microorganisms in plant material nutrition – current knowledge and future directions. *Front. Plant Sci.* 8: 16-17.

Jenny, H. 1941. *Factors of Soil Formation*: *A System of Quantitative Pedology.* McGraw-Hill. New York.

Johns, C. 2017. *Living Soils: The Role of Microorganisms in Soil Health. Future Directions*. International Pty Ltd, Hampden Road, Nedlands WA 6009. Australia.

Juma, N.G. 1998. *The pedosphere and its dynamics: a systems approach to soil science.* Quality Color Press Inc. Edmonton, Canada.

Kalam, S., Basu, A., Ahmad, I., Sayyed, R.Z., El-Enshasy, H.A., Dailin, D.J. and Suriani, N.L. 2020. Recent understanding of soil Acidobacteria and their ecological significance: A critical review. *Front. Microbiol.* 11: 580024.

Kalani, W., Girija, D. and Surendra, K. 2021. Native Multiphasic Plant Growth Promoting Rhizobacteria Consortia for Growth and Yield of Rice. *Res. Jr. of Agril. Sci*. 12: 601-606.

Kallenbach, C.M., Frey, S.D. and Grandy, A.S. 2016. Direct evidence for microbial-derived soil organic matter formation and its ecophysiological controls. *Nat. Commun*. 7: 13630.

Karmakar, R., Das, I., Dutta, D. and Rakshit, A. 2016. Potential Effects of Climate Change on Soil Properties: A Review. *Int. J. Sci.* 4(2): 51-73.

Kour, D., Kaur, T., Devi, R., Yadav, A., Singh, M., Joshi, D., Singh, J., Suyal, D.C., Kumar, A., Rajput, V.D., Yadav, A.N., Singh, K., Singh, J., Sayyed, R.Z., Arora, N.K. and Saxena, A.K. 2021. Beneficial microbiomes for bioremediation of diverse contaminated environments for environmental sustainability: Present status and future challenges. *Environ. Sci Pollut. Res*. 28: 24917–24939.

Krupenikov, I., Boincean, B., Dent, D., Boincean, B. and Dent, D. 2011. *Humus-Guardian of Fertility and Global Carbon Sink. The Black Earth: Ecological Principles for Sustainable Agriculture on Chernozem Soils*. International Year of Planet Earth, Springer, Dordrecht, The Netherlands.

Lal, R. 1998. Degradation and resilience of soils. p. 137-150. In: Greenland, D.J., Gregory, P.J. and Nye, P.H. (Edited) *Land Resources: On the Edge of the Malthusian Precipice?* Philosophical Transactions of Royal Society of London, CAB International, Wallingford, UK.

Lal, R. 2015. Restoring Soil Quality to Mitigate Soil Degradation. *Sustainability*. *7*(5): 5875-5895.

Lal, R. 2014. Societal value of soil carbon. *J. Soil Water Conserv. 69*(6): 186A–192A.

Lal, R. 2009. Soil degradation as a reason for inadequate human nutrition. *Food Sec.* 1: 45–57.

Lal, R. and Stewart, B.A. 1990. *Soil Degradation*. Springer-Verlag, New York, NY, USA.

Leifheit, E., Veresoglou, S., Lehmann, A., Morris, E.K. and Rillig, M. 2014. Multiple factors influence the role of arbuscular mycorrhizal fungi in soil aggregation—a meta-analysis. *Plant Soil.* 374: 523-537.

Liang, C., Schimel, J.P. and Jastrow, J.D. 2017. The importance of anabolism in microbial control over soil carbon storage. *Nat. Microbiol.* 2: 17105.

Loccos, M.Y., Macingui, P., Combes, C., Normand, P. and Steinberg, C. 2014. Microorganisms and Biotic Interactions. p. 395-444. In: Bertrand, J.C., Caumette, P., Lebaron, P., Matheron, R., Normand, P. and Sime-Ngando, T. (Edited) *Environmental Microbiology: Fundamentals and Applications*, Springer, Dordrecht.

Lutz, W., Sanderson, W. and Scherbov, S. 2001. The end of world population growth. *Nature*. 412: 543-545.

Lynch, J.M. 1983. *Soil Biotechnology*. Blackwell, Oxford.

Malhotra, J., Aparna, K., Dua, A., Sangwan, N., Trimurtulu, N., Rao, D.L.N. and Lal, R. 2015. Microbial and genetic ecology of tropical Vertisols under intensive chemical farming. *Environ. Monit. Assess.* 187: 4081.

Manlay, R., Feller, C. and Swift, M. 2007. Historical evolution of soil organic matter concepts and their relationships with the fertility and sustainability of cropping systems. *Agric. Ecosyst. Environ.* 119(3-4): 217–233.

Mason, J. 2003. *Sustainable Agriculture,* 2nd edition. Landlinks Press, Australia.

McCauley, A., Jones, C. and Olson-Rutz, K. 2017. *Soil pH and Organic matter.* Nutrient Management-Module No 8, Montana State University.

Medina, A., Roldán, A. and Azcón, R. 2010. The effectiveness of arbuscular-mycorrhizal fungi and *Aspergillus niger* or *Phanerochaete chrysosporium* treated organic amendments from olive residues upon plant growth in a semi-arid degraded soil. *J. Environ. Manage*. 91(12): 2547-2553.

Mikkuta, R., Mikkuta, C., Kalbitz, K., Scheel, T., Kaiser, K. and Jahn, R. 2007. Biodegradation of forest floor organic matter bound to minerals via different binding mechanisms. *Geochim. Cosmochim. Acta.* 71(10): 2569–2590.

Miltner, A., Bombach, P., Schmidt-Brücken, B. and Kästner, M. 2012. SOM genesis: microbial biomass as a significant source. *Biogeochemistry.* 111: 41-55.

Mohammadi, K., Heidari, G., Khalesro, S. and Sohrabi, Y. 2001. Soil management, microorganisms and organic matter interactions: A review. *Afr. J. Biotechnol*. 10(86): 19840-19849.

Moreno, J., Bastida, F., Hernandez, T. and Garcia, C. 2008. Relationship between the agricultural management of a semi-arid soil and microbiological quality. *Commun. Soil Sci. Plant Anal.* 39(3-4): 421–439.

Nguyen, N. and Bruns, T. 2015. The microbiome of *Pinusmuricata* ectomycorrhizae: community assemblages, fungal species effects, and *Burkholderia* as important bacteria in multi-partnered symbioses.

Microb. Ecol. 69(4): 914-921.

Nishio, M. and Kusano, S. 1980. Fluctuation patterns of microbial numbers in soil applied with compost. *Soil Sci. Plant Nutr.* 26(4): 581-593.

Njoku, C. and Okoro, G.C. 2015. Effect of flooding on soil properties in Abakaliki South Eastern Nigeria. *Scholarly J. Agric. Sci*. 5(5): 165-168.

Oades, J.M. 1993. The role of biology in the formation, stabilization and degradation of soil structure. *Geoderma.* 56(1-4): 377 - 400.

Owen, D., Williams, A.P., Griffith, G.W. and Withers, P.J.A. 2015. Use of commercial bio-inoculants to increase agricultural production through improved phosphorous acquisition. *Appl. Soil Ecol.* 86(4): 41-54.

Parikh, S.J. and James, B.R. 2012. Soil: The Foundation of Agriculture. *Nat. Education Knowledge*. 3(10): 2.

Peinemann, N., Amiotti, N., Zalba, P. and Villamil, M.B. 2000. Effect of Clay Minerals and Organic Matter on the Cation Exchange Capacity of Silt Fractions. *J. Plant Nutr. Soil Sci.* 163(1): 47-52.

Rajan, K., Natarajan, A., Kumar, K., Badrinath, M. and Gowda, R. 2010. Soil organic carbon—the most reliable indicator for monitoring land degradation by soil erosion. *Curr. Sci.* 99(6): 823–827.

Rao, D., Aparna, M. and Mohanty, S.R. 2019. Microbiology and Biochemistry of Soil Organic Matter. Carbon Sequestration and Soil Health. *Indian J. Fertilizers.* 15(2): 124-138.

Rashid, M.I., Mujawar, L.H., Shahzad, T., Almeelbi, T., Ismail, I.M.I. and Oves, M. 2016. Bacteria and fungi can contribute to nutrients bioavailability and aggregate formation in degraded soils. *Microbiol. Res.* 183: 26-41.

Rawls, W.J., Pachepsky, Y., Ritchie, J.C., Sobecki, T.M. and Bloodworth, H. 2003. Effect of soil Carbon on soil water retention. *Geoderma.* 116(1-2): 61-76.

Report No: 1455, 2018. *Soil Health Status of Kerala in Post Flood Scenario*. Department of Soil Survey and Soil Conservation. Thiruvanathapuram, Kerala, India.

Rowell, D.L. 1994. *Soil Science Methods and Applications.* Department of Soil Science, University of Reading, Longman Group, UK.

Roxy, M.K., Ghosh, S., Pathak, A., Athulya, R., Mujumdar, M., Murtugudde, R., Terray, P. and Rajeevan, M. 2017. A threefold rise in widespread extreme rain events over central India. *Nat. Commun.* 8: 708.

Sarkar, B., Patra, A.K., Purakayastha, T.J. and Megharaj, M. 2009. Assessment of biological and biochemical indicators in soil under transgenic Bt and non-Bt cotton crop in a sub-tropical environment. *Environ. Monit. Assess.* 156 : 595-604.

Sayyed, R.Z., Patel, P.R. and Shaikh, S.S. 2015. Plant Growth Promotion and Root Colonization by EPS Producing *Enterobacter* sp. RZS5 under Heavy Metal Contaminated Soil. *Indian J. Exp. Biology.* 53(2): 116-123.

Schmidt, M.W., Torn, M.S., Abiven, S., Dittmar, T., Guggenberger, G., Janssens, I.A., Kleber, M., KögelKnabner, I., Lehmann, J., Manning, D.A. and Nannipieri, P. 2011. Persistence of soil organic matter as an ecosystem property. *Nature***.** 478: 49-56.

Shahzad, A., Ullah, S., Dar, A.A., Sardar, M.F., Mehmood, T., Tufail, M.A., Shakoor, A. and Haris, M. 2021. Nexus on climate change: Agriculture and possible solution to cope future climate change stresses. *Environ. Sci. Pollut. Res.* 28(12):14211-14232.

Shaikh, S.S., Reddy, M.S. and Sayyed, R.Z. 2016. *Plant growth-promoting rhizobacteria: An eco-friendly approach for sustainable agroecosystem*. Plant Soil-Microbes, Springer, Switzerland.

Spence, A., Simpson, A.J., Mcnally, D.J., Moran, B.W., McCaul, M.V., Hart, K., Paull, B. and Kelleher, B.P. 2011. The degradation characteristics of microbial biomass in soil. *Geochimi. Cosmochim. Acta*. 75(10): 2571-2581.

Stephen, B. 1993. *Flooding and its effect on Tree.* USDA Forest Service's Press, USA. Stevenson, F.J. 1986. *Cycles of Soil: Carbon, Nitrogen, Phosphorus, Sulfur, Micronutrients.* Wiley, New York.

Stevenson, F.J. 1994. *Humus chemistry. genesis, composition, reactions.* 2nd edition. Wiley Interscienc, New York, USA.

Surendra, K. 2010. Consortia of Arbuscular Mycorrhizal fungi for the management of bacterial wilt disease in susceptible tomato. *Veg. Sci.* 37(2): 205-207.

Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R. and Polasky, S. 2002. Agricultural sustainability and intensive production practices. *Nature*. 418: 671-677.

USDA, *Recommended soil health indicators and associated laboratory procedures*. Natural Resources Conservation Service, Soil Health Technical Note No. SHXXUSDA, Document no. 2018-19985. Department of Agriculture, United States.

Vaughan, D. and Malcolm, R.E. 1985. *Soil Organic Matter and Biological Activity*. Junk. Boston, MA.

Waksman, S.A. 1936. *Humus. Origin, Chemical Composition and Importance in Nature*. Williams and Wilkins, New York.

Wallenstein, M. 2017. *To restore our soil, feed the microbes*. *The Conversation*. Academic rigour journalistic flair, Collorado state University, Fort Collins, US.

Wilkinson, R.E. 2000. *Plant-environment interaction.* Marcel Dekker, Inc, 270 Madison Avenue, New York.