International Journal of Chemical Studies

P-ISSN: 2349–8528
E-ISSN: 2321–4902
IJCS 2017; 5(6): 1648-1656

Received: 15-09-2017
Accepted: 17-10-2017

Hina Khatoon
Department of Environmental Science, G.B. Pant University of Agriculture and Technology, Pantnagar (U.S. Nagar), Uttarakhand, India

Praveen Solanki
Department of Environmental Science, G.B. Pant University of Agriculture and Technology, Pantnagar (U.S. Nagar), Uttarakhand, India

Maitrayie Narayan
Department of Environmental Science, G.B. Pant University of Agriculture and Technology, Pantnagar (U.S. Nagar), Uttarakhand, India

Lakshmi Tewari
Department of Microbiology, G.B. Pant University of Agriculture and Technology, Pantnagar (U.S. Nagar), Uttarakhand, India

JPN Rai
Department of Environmental Science, G.B. Pant University of Agriculture and Technology, Pantnagar (U.S. Nagar), Uttarakhand, India

Correspondence
Hina Khatoon
Department of Environmental Science, G.B. Pant University of Agriculture and Technology, Pantnagar (U.S. Nagar), Uttarakhand, India

Role of microbes in organic carbon decomposition and maintenance of soil ecosystem

Hina Khatoon, Praveen Solanki, Maitrayie Narayan, Lakshmi Tewari and JPN Rai

Abstract
Soil organic carbon (SOC) is simultaneously a source and sink for nutrients and plays a vital role in soil fertility maintenance. Several Microorganisms are present in soil ecosystem and they have various properties to decompose the organic carbon fraction like Cellulose, lignin, hemicelluloses, chitin and lipids present in soil organic matter. Decomposition is a mostly microbially mediated process, although its actual rate and extend are influenced by environmental variables, including soil temperature, moisture, oxygen, nitrogen content, the quality and quantity of available carbon substrates as well as soil management. Decomposition of soil organic carbon (SOC) is a critical component of the global carbon cycle, and accurate estimates of SOC decomposition are important for forest carbon modeling and ultimately for decision making relative to carbon sequestration and mitigation of global climate change. The sensitivity of soil organic matter decomposition to global environmental change is a topic of prominent relevance for the global carbon cycle. This review discusses the major role of different microorganisms in organic carbon decomposition and maintenance of soil ecosystem.

Keywords: Soil organic carbon, decomposition, microorganisms, soil ecosystem.

1. Introduction

Organic matter is mainly present in the top 20–30 cm of most soil profiles and is essentially an array of organic macromolecules consisting principally of combinations of carbon, oxygen, hydrogen, nitrogen, phosphorus and sulphur [1]. Almost all organic matter in soil is directly and indirectly derived from plants via photosynthesis. Thus atmospheric carbon dioxide is transformed by reduction into simple and complex organic carbon compounds, which in combination with key nutrients enable the plant to function and grow. The most important pathways by which the fixed carbon is retained and ultimately transferred to the soil ecosystem are the direct addition of senescent material as above-ground and below-ground detritus, return of ingested plant matter in animal faeces, and exudation of soluble organic compounds from roots [2].

Plant and animal detritus and root exudates represent essential sources of energy and nutrients for soil microbial and faunal communities. Bacteria and fungi represent 95%+ of the biomass present in most soils, where they interact with a combination of micro-fauna (nematodes, protozoa), meso-fauna (acari, Collembola, mites) and macro-fauna (earthworms, termites, molluscs) in complex soil food-web systems that determine the turnover of organic matter and associated nutrients in the soil environment [3, 4]. Decomposition depends on multiple factors that are being altered simultaneously as a result of global environmental change; therefore, it is important to study the sensitivity of the rates of soil organic matter decomposition with respect to multiple and interacting drivers.

2. Soil Organic Carbon

Soil organic carbon is organic component of soil, consisting of three primary parts including small (fresh) plant residues and small living soil organisms, decomposing (active) organic matter, and stable organic matter (humus) and Soil organic carbon (TOC) is the carbon (C) stored in soil organic matter (SOM). Organic carbon (OC) enters the soil through the decomposition of plant and animal residues, root exudates, living and dead microorganisms, and soil biota. It is the main source of energy for soil microorganisms.

3. Soil organic matter

The soil organic matter (SOM) is a complex combination of living organisms, fresh organic residues, actively decomposing material, and stabilized organic matter (otherwise known as humus). Generally, samples containing 50% or more of carbon are referred as soil organic carbon (SOC). Soil organic matter (SOM) is mainly composed of carbon, hydrogen and oxygen but also has small amounts of nutrients such as nitrogen, phosphorous, sulphur, potassium, calcium and magnesium contained within organic residues.
Soil organic matter also exists as four distinct fractions which vary widely in their in size, composition and turnover times in the soil (Table 1).

Table 1: The size, turnover rate and composition of the four soil organic matter fractions.

Fraction	Size micrometres (μm) & millimetres (mm)	Turnover time	Composition
Dissolved organic matter	<45 (μm) (in solution)	Minutes to days	Soluble root exudates, simple sugars and decomposition by-products. It generally makes up less than 5% of total soil organic matter.
Particulate organic matter	53μm–2mm	2-50 years	Fresh or decomposing plant and animal matter with identifiable cell structure. Makes up between 2-25% of total soil organic matter.
Humus	<53μm	Decadal (0s-00s years)	Older, decayed organic compounds that have resisted decomposition. Can make up more than 50% of total soil organic matter.
Resistant organic matter	<53μm <2mm	00s-000s years	Relatively inert material such as chemically resistant materials or organic remnants (for example, charcoal). Can be up to 10% of soil organic matter.

4. How is soil organic matter different to soil organic carbon?

Soil organic carbon (SOC) is different to organic matter because it refers only to the carbon component of organic compounds. Soil organic matter is difficult to measure directly, so laboratories tend to measure and report soil organic carbon. A conversion factor is available to report soil organic matter when required.
About 58% of the mass of organic matter exists as carbon. So if we know the organic carbon content in a soil we can estimate the amount of organic matter:
Organic matter (%) = total organic carbon (%) x 1.72
While this ratio can vary in different soils, using a conversion factor of 1.72 provides a reasonable estimate of soil organic matter and is suitable for most purposes.
Soil organic carbon stock in tonnes of carbon per hectare (tCha) = total organic carbon (%) x mass of soil in a given volume (bulk density)
As an example, in a soil with a soil organic carbon of 1.5% and a bulk density of 1.4 grams per cubic centimetre (g/cm^3) the amount of soil organic carbon to a depth of 10cm would be:
1.5 x 1.4 x 10 = 24 tCha.
Using the conversion factor of 1.72 the amount of soil organic matter would be: 24 x 1.72 = 41.28 tonnes of organic matter [5].

5. Where Does SOM come from?

SOM comes either from plant and crop residues, such as stems, leaves, or shoots, or indirectly from sewage or manure, Animal tissue and excretory products etc. There are two parts in the SOM, the "living" part and "nonliving" part. The "living" part of SOM consists bacteria, fungi, and insects; the "nonliving" part of SOM includes dead plants, animal matters, and excreta from soil organisms. The non-living soil organic matter can be divided into a number of fractions based on a combination of physical size and chemical form [6].

6. Humus or stable Organic matter

Complex organic compounds that remain after many organisms have used and transformed the original organic material leaving a stable form. Humus is important in binding tiny soil aggregates, and improves water and nutrient holding capacity. Humus is a combination of many compounds, and is critical in defining many properties of a soil. It increases water and nutrient retention, encourages aggregate formation, and inhibits impaction. Humus is composed mainly of humin, humic acid, and fulvic acid. Two major methods of humus formation are by minor modifications of lignin and by the degradation and reassembly of plant residues (lignin, cellulose, hemicellulose) by extracellular enzymes. Humus is a very stable, long-lived pool of organic matter in the soil with a turnover rate of 100-500 years.

7. Soil Organic matter in Peat and mineral soil

7.1. Peat

Peat is an accumulation of partially decayed vegetation or organic matter that is unique to natural areas called peat lands, bogs, or mires [7, 8]. The peatland ecosystem is the most efficient carbon sink on the planet because peatland plants capture the CO_2 which is naturally released from the peat, thus maintaining an equilibrium. In natural peatlands, the "annual rate of biomass production is greater than the rate of decomposition", but it takes "thousands of years for peatlands to develop the deposits of 1.5 to 2.3 m, which is the average depth of the boreal peatlands" [8]. Soils that contain mostly peat are known as histosols. Peat forms in wetland conditions, where flooding obstructs flows of oxygen from the atmosphere, slowing rates of decomposition [9].

7.2. Mineral soil

A soil derived from minerals or rocks and containing little humus or organic matter. Soil composed principally of mineral matter, in which the characteristics of the soil are determined more by the mineral than by the organic content. Soil minerals play a vital role in soil fertility since mineral surfaces serve as potential sites for nutrient storage. However, different types of soil minerals hold and retain differing amounts of nutrients.

8. Soil organic matter decomposition

When plant residues are returned to the soil, various organic compounds undergo decomposition. Decomposition is a biological process that includes the physical breakdown and biochemical transformation of complex organic molecules of dead material into simpler organic and inorganic molecules [10]. The continual addition of decaying plant residues to the soil surface contributes to the biological activity and the carbon cycling process in the soil. Breakdown of soil organic matter and root growth and decay also contribute to these processes. Carbon cycling is the continuous transformation of organic and inorganic carbon compounds by plants and micro- and macro-organisms between the soil, plants and the atmosphere. Decomposition of organic matter is largely a biological process that occurs naturally. Its speed is determined by three major factors: soil organisms, the physical environment and the quality of the organic matter [11]. In the decomposition process, different products are released: carbon dioxide (CO_2), energy, water, plant nutrients and resynthesized organic carbon compounds. Successive decomposition of dead material and modified organic matter results in the formation of a more complex organic matter called humus [10]. Humus affects soil properties. As it slowly decomposes, it colours the soil darker, increases soil aggregation and aggregate stability, increases the ability to attract and retain nutrients and contributes N, P and other nutrients.

9. Microbiological Aspects of organic matter decomposition

Organic matter decomposition is primarily a microbiological process. Decomposition is carried out by heterotrophic microflora and microfauna comprising bacteria, fungi, actino-mycetes and protozoa. In contrast to autotrophic organisms which can synthesize their own food from simple substances, heterotrophs derive energy and carbon for their growth solely from organic compounds. Besides the microflora and microfauna, many species of mesofauna such as earthworms also play an important role in the initial breakdown of organic residues. Organic matter decomposition serves three functions for the microflora: (i) providing energy for growth, (ii) supplying carbon for the formation of cell material, and (iii) providing other nutrient, elements needed for cell growth.

10. Enzymes for Organic matter decomposition

Organic matter decomposition is largely an enzymatic process. Constitutional enzymes are produced by microbial cells, irrespective of the substrate in the environment; inducible enzymes are formed in the presence of a specific substrate. Further, an enzyme may metabolize its substrate within or outside the cell. Accordingly, they are known as intracellular or extracellular enzymes. Extracellular enzymes are essential for the decomposition of polysaccharides because the microbial cell is impenetrable to the large polysaccharide molecules. Monosaccharides, such as glucose, are metabolized by intracellular enzymes. Organic residues added to the soil are first broken down into their basic components by extracellular enzymes; and the basic components are subsequently utilized by intracellular enzymes.

11. Interactions between Microorganisms and Soil Fauna

The role of microorganisms in formation and decomposition of soil organic matter cannot be discussed without reference to the interactions of microorganisms with the soil micro- and macrofauna. A diverse range of biota is present in soil, including micro-fauna (e.g., nematodes and protozoa), meso-fauna (e.g., Collembola, mites and acari) and macro-fauna (e.g., earthworms, molluscs and termites). The impact of invertebrates on soil organic matter turnover has been studied since Darwin's pioneering work [12]. However, despite the importance of soil fauna in organic matter breakdown being well recognised, the complex interactions between soil fauna and microorganisms and the indirect effect on microfauna and microbial communities are less well understood. While soil invertebrates mediate about 15% of the carbon and 30% of the nitrogen turnover in a range of ecosystems [13].

The interactions between soil microflora and fauna have been most well studied in earthworms. However, other groups of soil-inhabiting invertebrates undoubtedly play a significant role in formation and turnover of organic matter, in particular mesoarthropods such as mites and Collembola. The extent to which these various groups of soil fauna control decomposition may depend on the ecosystem. For example, microarthropods that feed on fungi, especially Collembola, can play a key role in no-tillage agroecosystems, but are less important in conventionally tilled systems [14]. Few studies have been carried out but it seems likely that, like the earthworms, microarthropods can play key roles in influencing the activities of microorganisms in organic matter processing in soil [15]. It is well established that there are larger populations of fungi, bacteria and actinomycetes, and higher enzymatic activity in earthworm casts than in bulk soil. Higher proportions of cellulolytic, hemicellulolytic, nitrifying and denitrifying bacteria and larger, more diverse fungal populations have been recovered from casts than surrounding soil [16]. Soils in terrestrial ecosystems are major carbon sinks. This pool of organic carbon is of particular interest because even small changes in flux rates into or out of pools of soil organic matter could have a strong influence on atmospheric carbon dioxide concentrations and associated climate change.

12. Decomposition of Organic Matter and the Microbes Involved

The insoluble plant residues constitute the part of humus and soil organic matter complex. The final product of aerobic decomposition is CO_2 and that of anaerobic decomposition are Hydrogen, ethyl alcohol (CH_4), various organic acids and carbon dioxide (CO_2). Soil organisms use organic matter as a source of energy and food [17].

The process of decomposition is initially fast, but slows down considerably as the supply of readily decomposable organic matter gets exhausted. Sugars, water-soluble nitrogenous compounds, amino acids, lipids, starches and some of the hemicellulases are decomposed first at rapid rate, while insoluble compounds such as cellulose, hemicellulose, lignin, proteins etc. which forms the major portion of organic matter are decomposed later slowly. Thus, the organic matter added to the soil is converted by oxidative decomposition to simpler substances which are made available in stages for plant growth and the residue is transformed into humus. The microbiology of decomposition/degradation of some of the major constituents of soil organic matter/plant residues are discussed in brief in the following paragraphs:

12.1 Cellulose decomposition

Cellulose is the most abundant carbohydrate present in plant residues/organic matter in nature. When cellulose is associated with pentosans (eg. xylans & mannans) it undergoes rapid decomposition, but when associated with lignin, the rate of decomposition is very slow. The decomposition of cellulose occurs in two stages: (i) in the first stage the long chain of cellulase is broken down into cellobiase and then into glucose by the process of hydrolysis in the presence of enzymes cellulase and cellobiase, and (ii) in second stage glucose is oxidized and converted CO_2 and water (fig.1).

Cellulose is a structural polysaccharide that contains glucose. In order to access this glucose for catabolism, the cellulose must be decomposed by extracellular enzymes. These pieces are then transported into the cell for energy generation (catabolism) or production of biomass (anabolism). Fungi such as *Penicillium* and *Aspergillus* and bacteria such as *Streptomyces* and *Pseudomonas* are important participants in the extracellular cleavage of cellulose (sylvia, 2005). The most extensively studied sources of cellulolytic enzymes have been the fungi *Trichoderma* and *Phanerochaete* and the bacteria *Cellulomonas* (an aerobe) and *Clostridium thermocellum* (an anaerobe).

Enzymes

Fungi produces three types of cellulolytic enzymes that cooperate in the degradation of cellulose: endoglucanases (EG I to EG V), cellobiohydrolases (CBH I and CBH II), and *β*-glucosidases (BGL I and BGL II).

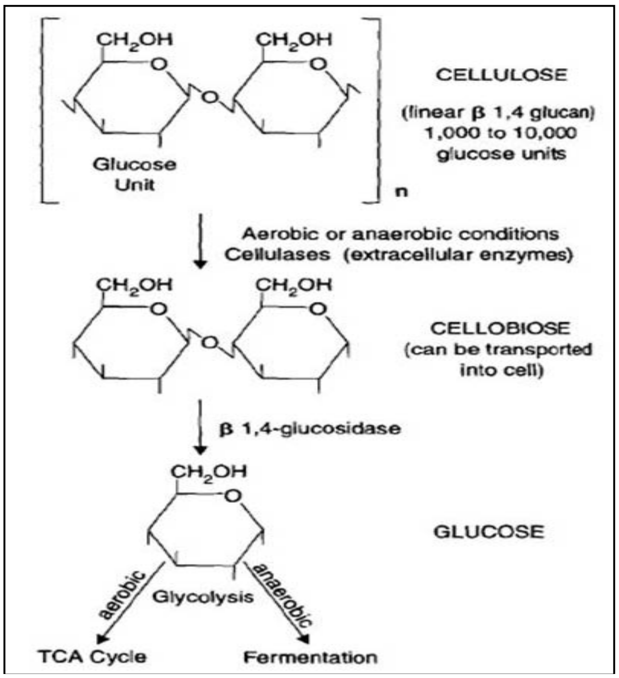

Fig 1: The decomposition of Cellulose [18].

12.2 Hemicellulose decomposition

Hemicelluloses are water-soluble polysaccharides and consists of hexoses, pentoses, and uronic acids and are the major plant constituents second only in quantity of cellulose, and sources of energy and nutrients for soil microflora. The hydrolysis is brought about by number of hemicellulolytic enzymes known as "hemicellulases" excreted by the microorganisms. On hydrolysis hemicelluloses are converted into soluble monosaccharide/sugars (eg. xylose, arabinose, galactose and mannose) which are further convened to organic acids, alcohols, CO_2 and H_2O and uronic acids are broken down to pentoses and CO_2 (fig.2). Various microorganisms including fungi, bacteria and actinomycetes both aerobic and anaerobic are involved in the decomposition of hemicelluloses. Even though hemicelluloses decomposition is much quicker than cellulose decomposition, cells will utilize simple as substrates before hemicelluloses [18].

Enzymes

Hemicellulases are xylanases, mannanases, arabinofuranosides, and pectin lyases.

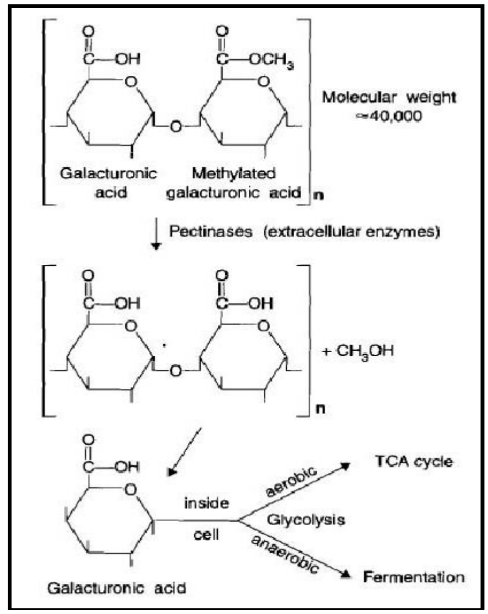

Fig 2: The decomposition of Hemicellulose [18].

12.3 Chitin decomposition

Chitin is a special compound which can be found in the integument of arthropods and cell wall of fungi. The polymer is not easily degraded, and requires a variety of enzymes to do so [18]. Fig.3 shows the decomposition process of chitin and chitosan. The dominant chitin degrades are the *actinomycetes Streptomyces* and *Nocardia,* and (less importantly) fungi as *Trichoderma* and *Verticillium.*

Enzymes

Microbes produced Chitinase enzymes for chitin degredation and Chitosanase for chitosan degradation.

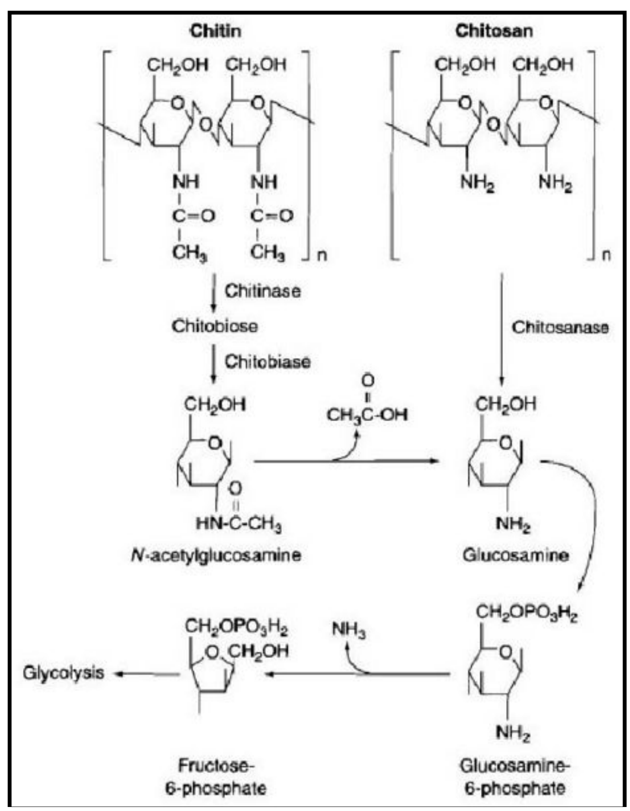

Fig 3: The decomposition of Chitin [18].

12.4 Lignin decomposition

Lignin is the third most abundant constituent of plant tissues, and accounts about 10-30 percent of the dry matter of mature plant materials. Lignin content of young plants is low and gradually increases as the plant grows old. It is one of the most resistant organic substances for the microorganisms to degrade however certain Basidiomycetous fungi are known to degrade lignin at slow rates. The final cleavages of these aromatic compounds yield organic acids, carbon dioxide, methane and water (fig.4, fig.5). Lignin is the main component of wood in trees. Lignin has a varied, unique, and complicated chemical structure which contains many aromatics. These aromatics can be released from the lignin structure by fungal enzymes such as peroxidises and oxidases. The enzymes utilize H_2O_2 and OH radicals to break the bonds in the lignin. Common types of fungi which degrade lignin are white rot (*Phanerochaete chrysosporium*), brown rot, and soft rot. Once the aeromatics are released from the original lignin structure they are incorporated into the metabolic pathway as pyruvate, acetyl CoA, and into the TCA cycle [18].

Enzymes

Lignin peroxidise, Mn(II)-Dependent Peroxidases, Quinone Reductases are produced by microbes for lignin degredation.

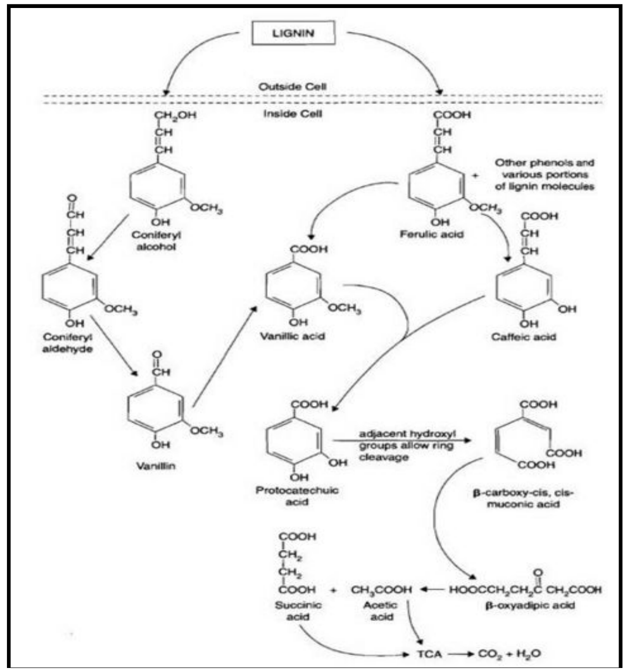

Fig 4: The decomposition of lignin [18].

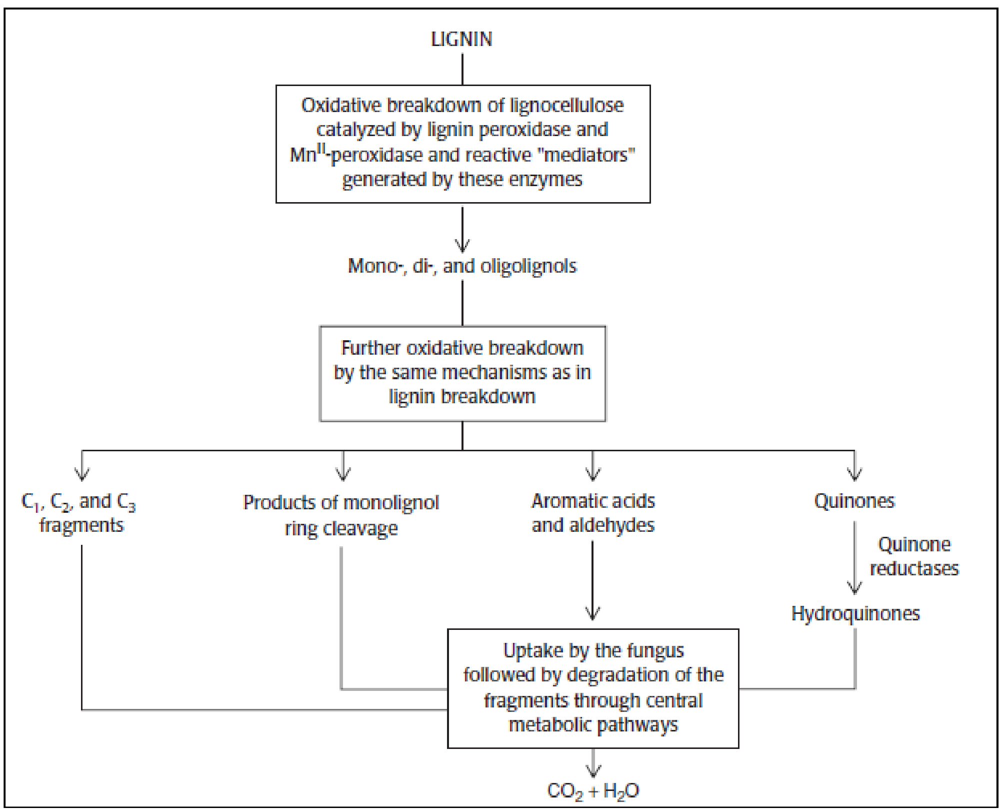

Fig 5: Role of different enzymes in lignin degredation.

12.5 Lipids decomposition

Soil lipids, a complex series of 500 different fatty acids, are mostly derived from plants and microorganisms. The lipid content of soil organic matter ranges from 2% to 20%. Phospholipids are the primary lipids composing cellular membranes.

Enzymes

Phospholipases are enzymes that degrade phospholipids through hydrolytic cleavage of carboxy- and phospho-diester bonds. Phospholipases A, B lipases fatty acid esters and Phospholipases of the C, D types cleave phosphate ester bonds.

12.6 Protein Decomposition

Proteins are complex organic substances containing nitrogen, sulphur, and sometimes phosphorus in addition to carbon, hydrogen and oxygen. During the course of decomposition of organic matter, proteins are first hydrolyzed to a number of intermediate products eg. Proteases, peptides etc. collectively known as polypeptides. The intermediate products so formed are then hydrolyzed and broken down ultimately to individual amino acids, or ammonia and amides. The process of hydrolysis of proteins to amino acids is known as “aminization or ammonification”, which is brought about by certain enzymes, collectively known as “proteases” or “proteolytic” enzymes secreted by various microorganisms. Amino acids and amines are further decomposed and converted into ammonia. During the course of ammonification, various organic acids, alcohols, aldehydes etc. are produced which are further decomposed finally to produce carbon dioxide and water.

13. Release of atmospheric CO_2 by organic carbon decomposition

Decomposition of organic carbon in soil is driven primarily by the activities of bacteria and fungi, while only 10–15% of soil carbon flux can be directly attributed to the actions of fauna [6]. The vast majority of soil microorganisms are heterotrophs that rely on organic matter for energy and nutrients. These can be divided into microorganisms that respond primarily to the addition of fresh carbon substrates (zymogenous or *r*-selected biomass) and those that derive their energy mainly from the decomposition of older, more recalcitrant forms of organic carbon (autochthonous or *K*-selected biomass) [6].

Plants benefit directly from exudate enhanced biological activity in the rhizosphere, mainly via improved acquisition of sparingly soluble and organic soil nutrients mobilised by microorganisms in response to the provision of energy-rich carbon substrate. This includes the specific symbiotic relationship between plant roots and mycorrhizal fungi, whereby fungi living in close association with plant root cells obtain a supply of soluble carbon from the plant (up to 20% of assimilated carbon) in exchange for improved access to and mobilisation of sparingly-soluble mineral and organic forms of soil nutrients. In most natural and managed ecosystems up to half of the organic carbon added to soil on an annual basis in plant detritus and root exudates is rapidly consumed by microbial and faunal activity and released as carbon dioxide (fig.6).

The availability of soil organic C for microbial decomposition is crucial for many processes within the C cycle since it controls the rate of CO_2 flux to the atmosphere, determines the sources contributing to soil CO_2, affects microbial activity and composition, and reflects C sequestration. Soil organic C consists of various heterogeneous pools which differ in their stability and availability and are characterized by particular turnover rates. Older, more recalcitrant C pools are less decomposable by microorganisms in comparison to younger C pool. According to their turnover time various C pools contribute differently to soil CO_2 as the major product of microbial decomposition. The terrestrial carbon cycle is dominated by the balance between photosynthesis and respiration.

Carbon is transferred from the atmosphere to soil via ‘carbon-fixing’ autotrophic organisms, mainly photosynthesising plants and also photo and chemoautotrophic microbes that synthesise atmospheric carbon dioxide (CO_2) into organic material. Fixed carbon is then returned to the atmosphere by a variety of different pathways that account for the respiration of both autotrophic and heterotrophic organisms. The reverse route includes decomposition of organic material by ‘organic carbon-consuming’ heterotrophic microorganisms that utilise the carbon of either plant, animal or microbial origin as a substrate for metabolism, retaining some carbon in their biomass and releasing the rest as metabolites or as CO_2 back to the atmosphere.

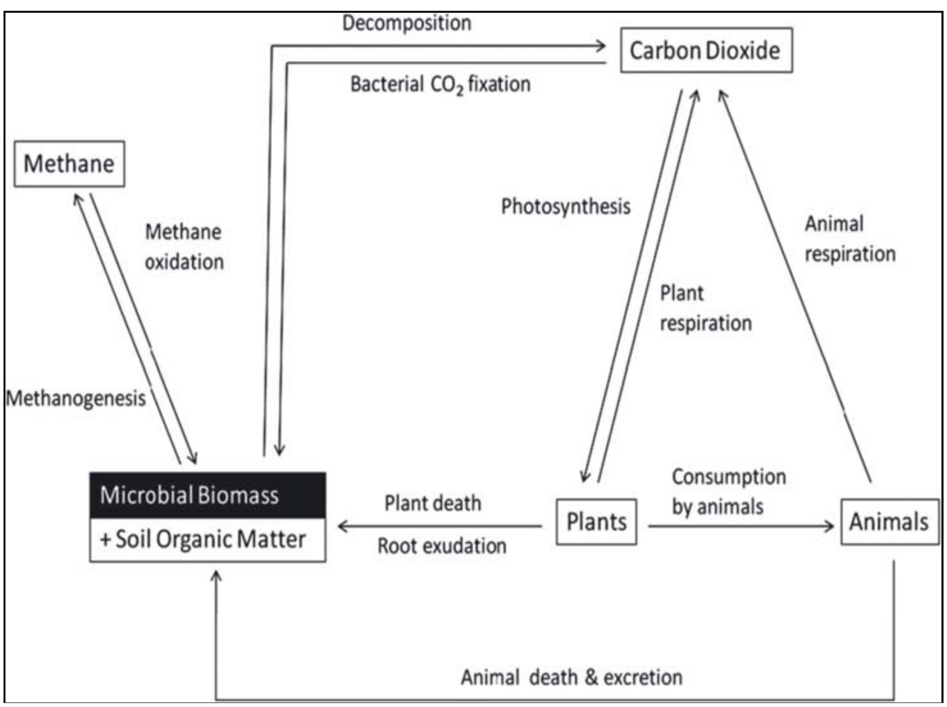

Fig 6: The terrestrial carbon cycle with the major processes mediated by soil microorganisms.

14. Microbial respiration for maintenance of carbon in ecosystem

Soil respiration refers to the production of carbon dioxide when soil organisms respire. This includes respiration of plant roots, the rhizosphere, microbes and fauna. Soil respiration is a key ecosystem process that releases carbon from the soil in the form of CO_2. CO_2 is acquired from the atmosphere and converted into organic compounds in the process of photosynthesis. Plants use these organic compounds to build structural components or respire them to release energy. When plant respiration occurs below-ground in the roots, it adds to soil respiration. Soil respiration and its rate across ecosystem are extremely important to understand. This is because soil respiration plays a large role in global carbon cycling as well as other nutrient cycles.

14.1 Sources of carbon dioxide in soil

All cellular respiration releases energy, water and CO2 from organic compounds. Any respiration that occurs below-ground is considered soil respiration. Respiration by plant roots, bacteria, fungi and soil animals are all sources of 2 to 20 millimeters (0.08 to 0.8 in) in soil

14.1.1. Tricarboxylic acid (TCA) cycle

The tricarboxylic acid (TCA) cycle — or citric acid cycle is an important step in cellular respiration. In the TCA cycle, a six carbon sugar will be oxidized [19]. This oxidation produces the CO_2, and H_2O from the sugar. Plants, fungi, animals and bacteria all use this cycle to convert organic compounds to energy. This is how the majority of soil respiration occurs at its most basic level. Since the process relies on oxygen to occur. This is referred to as aerobic respiration

14.1.2. Fermentation

Fermentation is another process in which cells gain energy from organic compounds. In this metabolic pathway, energy is derived from the carbon compound without the use of oxygen. The products of this reaction are carbon dioxide and usually either ethyl alcohol or lactic acid [20]. Due to the lack of oxygen, this pathway is described as anaerobic respiration. This is an important source of CO_2 in soil respiration in waterlogged ecosystems where oxygen is scarce, as in peat bogs and wetlands. However, most CO_2 released from the soil occurs via respiration and one of the most important aspects of below- ground respiration occurs in the plant roots.

14.2 Role of Plant roots in soil respiration

Plants respire some of the carbon compounds which were generated by photosynthesis. When this respiration occurs in roots, it adds to soil respiration. Root respiration usually accounts for approximately half of all soil respiration. However, these values can range from 10–90% depending on the dominate plant types in an ecosystem and conditions under which the plants are subjected. Thus the amount of CO_2 produced through root respiration is determined by the root biomass and specific root respiration rates [21].

14.3 Role of rhizosphere in soil respiration

The rhizosphere is a zone immediately next to the root surface with its neighboring soil. In this zone there is a close interaction between the plant and microorganisms. Roots continuously release substances, or exudates, into the soil. These exudates include sugars, amino acids, vitamins, long chain carbohydrates, enzymes and lysates which are released when roots cells break. The amount of carbon lost as exudates varies considerably between plant species. It has been demonstrated that up to 20% of carbon acquired by photosynthesis is released into the soil as root exudates [22]. These exudates are decomposed primarily by bacteria. These bacteria will respire the carbon compounds through the TCA cycle; however, fermentation is also present. This is due to the lack of oxygen due to greater oxygen consumption by the root as compared to the bulk soil, soil at a greater distance from the root [23]. Another important organism in the rhizosphere are root-infecting fungi or mycorrhizae. These fungi increase the surface area of the plant root and allow the root to encounter and acquire a greater amount of soil nutrients necessary for plant growth. In return for this benefit, the plant will transfer sugars to the fungi. The fungi will respire these sugars for energy thereby increasing soil respiration [24].

14.4 Role of Soil Biota in soil respiration

Soil animals graze on populations of bacteria and fungi as well as ingest and break up litter to increase soil respiration. Microfauna are made up of the smallest soil animals. These include nematodes and mites. This group specializes on soil bacteria and fungi. By ingesting these organisms, carbon that was initially in plant organic compounds and was incorporated into bacterial and fungal structures will now be respired by the soil animal. Mesofauna are soil animals from 0.1 to 2 millimeters (0.0039 to 0.0787 in) in length and will ingest soil litter. The fecal material will hold a greater amount of moisture and have a greater surface area. This will allow for new attack by microorganisms and a greater amount of soil respiration. Macrofauna are organisms from 2 to 20 millimeters (0.079 to 0.787 in), such as earthworms and termites. Most macrofauna fragment litter, thereby exposing a greater amount of area to microbial attack. Other macrofauna burrow or ingest litter, reducing soil bulk density, breaking up soil aggregates and increasing soil aeration and the infiltration of water [25].

15. The soil food web

The soil ecosystem can be defined as an interdependent life-support system composed of air, water, minerals, organic matter, and macro- and micro-organisms, all of which function together and interact closely. The organisms and their interactions enhance many soil ecosystem functions and make up the soil food web. The energy needed for all food webs is generated by primary producers: the plants, lichens, moss, photosynthetic bacteria and algae that use sunlight to transform CO_2 from the atmosphere into carbohydrates. Most other organisms depend on the primary producers for their energy and nutrients; they are called consumers.

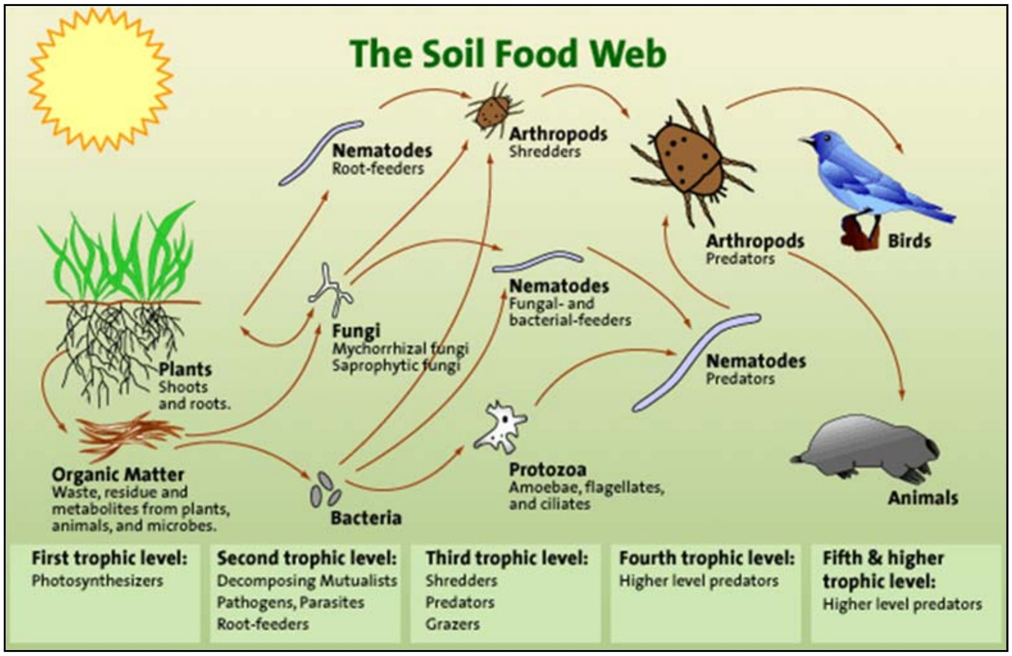

Fig 7: The soil food web showing maintenance of soil ecosystem [29].

The soil food web is the community of organisms living all or part of their lives in the soil. It describes a complex living system in the soil and how it interacts with the environment, plants, and animals. Food webs describe the transfer of energy between species in an ecosystem. While a food chain examines one, linear, energy pathway through an ecosystem, a food web is more complex and illustrates all of the potential pathways. Much of this transferred energy comes from the sun. Plants use the sun's energy to convert inorganic compounds into energy-rich, organic compounds, turning carbon dioxide and minerals into plant material by photosynthesis. Plant flowers exude energy-rich nectar above ground and plant roots exude acids, sugars, and ectoenzymes into the rhizosphere, adjusting the pH and feeding the food web underground [26-28]. Soil life plays a major role in many natural processes that determine nutrient and water availability for agricultural productivity. The primary activities of all living organisms are growing and reproducing. By-products from growing roots and plant residues feed soil organisms. In turn, soil organisms support plant health as they decompose organic matter, cycle nutrients, enhance soil structure and control the populations of soil organisms, both beneficial and harmful (pests and pathogens) in terms of crop productivity (Fig.7).

16. Acknowledgement

The overall implementation of this study including literature collection and manuscript preparation were done by Hina Khatoon, Praveen Solanki, Maitreyie Narayan, Lakshmi Tewari and J.P.N. Rai. Hina Khatoon and Lakshmi Tewari critically reviewed the article. All authors read and approved the final manuscript.

17. References

1. Baldock J. Composition and cycling of organic carbon in soil. In: Marschner P, Rengel Z (eds) Nutrient cycling in terrestrial ecosystems. Springer, Berlin, Germany, 2007, 1-36.
2. Howarth W. Carbon cycling and formation of organic matter. In: Paul EA (ed) Soil microbiology, ecology, and biochemistry, 3rd edn. Academic Press, Amsterdam, The Netherlands, 2007, 303-340.
3. Wardle DA, Nilsson MC, Zackrisson O. Fire-derived charcoal causes loss of forest humus. Science. 2008; 320:629.
4. Coleman D, Wall D. Fauna: the engine for microbial activity and transport. In: Paul E (ed) Soil microbiology, ecology, and biochemistry. Academic Press, Amsterdam, The Netherlands, 2007, 163-194.
5. Griffin E, Hoyle FC, Murphy DV. Soil organic carbon in Report card on sustainable natural resource use in Agriculture, Department of Agriculture and Food, Western Australia, 2013, 46.
6. Hopkins DW, Gregorich EG. Carbon as a substrate for soil organisms. In: Bardgett RD, Usher MB, Hopkins DW (eds) Biological diversity and function in soils. Cambridge University Press, Cambridge, UK, 2005, 57-79.
7. Joosten H, Clarke D. Wise Use of Mires and Peatlands: Background and Principles including a Framework for Decision-Making (Report). Totnes, Devon. ISBN 951-97744-8-3, 2002.
8. Hugron Sandrine, Bussières J, Rochefort L. Tree plantations within the context of ecological restoration of =peatlands: practical guide (Report). Laval, Québec, Canada: Peatland Ecology Research Group (PERG), 2014.
9. Keddy PA. Wetland Ecology: Principles and Conservation (2nd edition). Cambridge University Press, Cambridge, UK, 2010, 497(1).
10. Juma NG. The pedosphere and its dynamics: a systems approach to soil science. Edmonton, Canada, Quality Color Press Inc, 1998, 1:315.
11. Brussaard L. Interrelationships between biological activities, soil properties and soil management. In D.J. Greenland & I. Szabolcs, eds. Soil resilience and sustainable land use, Wallingford, UK, 1994, 309-329.
12. Darwin C. The formation of vegetable mould through the action of worms, with observations on their habit. In:

Ridely M (ed) The essential Darwin. Allen and Unwin, London, 1881, 237-256.
13. Anderson J. Soil organisms as engineers: microsite modulation of macroscale processes. In: Jones C, Lawton J (eds) Linking species and ecosystems. Chapman Hall, London, 1995, 94-106.
14. Hendrix PF, Parmelee RW, Crossley DA, Coleman DC, Odum EP, Groffman PM. Detritus food webs in conventional and no-tillage agroecosystems. Bioscience. 1986; 36:374-380.
15. Edwards C. Soil invertebrate controls and microbial interactions in nutrient and organic matter dynamics in natural and agroecosystems. In: Coleman D, Hendrix P (eds) Invertebrates as webmasters in ecosystems. CAB International, Wallingford, UK, 2000, 141-159.
16. Tiwari S, Mishra R. Fungal abundance and diversity in earthworm casts and in uningested soil. Biol Fert Soils. 1993; 16:131-134.
17. Han L, Sun K, Jin J, Xing B. Some concepts of soil organic carbon characteristics and mineral interaction. Soil Biology & Biochemistry. 2016; 94:107-121.
18. Sylvia DM, Fuharmann JJ, Hartel PG, Zuberer DA. Principles and applications of soil microbiology (2nd ed.). Upper Saddle River, N. J. Prentice Hall, 2005.
19. Berg J, Tymoczko J, Stryer L. Biochemistry. WH Freeman and Company, 2002.
20. Klein D, Prescott L, Harley J. Microbiology. McGraw-Hill, 2005.
21. Shibistova O, Lloyd J, Evgrafova S, Savushkina N, Zrazhevskaya G, Arneth A *et al*. Seasonal and spatial variability in soil CO_2 efflux rates for a central Siberian Pinus sylvestris forest. Tellus 54B, 2002, 552-567.
22. Hutsch B, Augustin J, Merbach W. Plant rhizodeposition-an important source for carbon turnover in soils. Journal of Plant Nutrition and Soil Science. 2002; 165(4):397-407.
23. Vance E, Chapin F. Substrate limitations to microbial activity in taiga forest floors. Soil Biology and Biochemistry. 2001; 33(2):173-188.
24. Harrison M. Peace Talks and Trade Deals. Keys to Long-Term Harmony in Legume-Microbe Symbioses. Plant Physiology. 2005; 137(4):1205-1210.
25. Chapin F, Matson P, Mooney H. Principles of terrestrial ecosystem ecology. Springer-Verlag, New York, 2002.
26. Marschner H. Mineral Nutrition of Higher Plants. ISBN 0124735436, 1995.
27. Walker TS, Bais HP, Grotewold E, Vivanco JM. Root Exudation and Rhizosphere Biology. Plant Physiology 2003; 132(1):44-51.
28. Power ML, Anne M, Burrows; Leanne T. Nash, eds. The Evolution of Exudativory in Primates / Nutritional and Digestive Challenges to Being a Gum-feeding Primate. Springer, 2012, 28.
29. USDA. Soil Biology Primer Photo Gallery. Natural Resources Conservation Service - Soils. Soil and Water Conservation Society, U.S. Department of Agriculture, 2016.