Food for thought: do soil microbes need food too? indeed, lest we don't need ours

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Increasing evidences indicate soil microorganisms are responsible for providing food to the world. However, less importance is given to satisfy food needs of millions and millions of soil microbes whose services support lives on Earth. Carbon, present as soil organic carbon, is the food for these microbes. In India, annually, hundreds of tonnes of carbon present in agro-wastes are squandered by burning them. Recycling agro-wastes is simplest strategy to return carbon to soils and provide food for the microbes. It will not be inappropriate to argue that a soil with good organic carbon content and microbial activities is fundamental to realize full benefit of all agricultural technologies aimed at improving food production. In this article, we reason out why and how 'putting food on table of soil microbes will supply food on our table'.

Keywords: Agro-waste recycling, food for microbes, soil microorganisms, soil organic carbon.

Food production depends on soil

'*Essentially, all life depends upon the soil ... There can be no life without soil and no soil without life; they have evolved together.*'

– Charles E. Kellogg

SOIL is the medium on which plants, the primary producers, grow and produce food for human beings, animals, birds and other terrestrial organisms. The Global Biodiversity Assessment document declares that soil is 'the critical life support surface on which all terrestrial biodiversity depends'[1]. Though cultivation exists on alternative media in the form of hydroponics[2], aeroponics[3]-based vertical farming[4], using compost[5] or coir dust[6] as substrata, soil will remain the fundamental and irreplaceable component of food production for many more decades. The service soils give to agriculture is enormous and two examples, out of many, highlight this: (a) the value of soils as supporting and anchoring media for plants can be understood by the fact that it would cost about US$ 55,000 just for the physical support trays and stands to grow plants in a 1 ha area through hydroponics system[7], and (b) the value of water and nutrient supplied by soil as measured by the cost of replacing lost water and nutrients due to soil erosion on agricultural land amounts to an estimated US$ 250 billion annually at global level[8]. In short, soil provides an array of ecosystem services that are so fundamental to life that their total value could only be expressed as infinite[9]. Soil, for a nation, therefore, is one of the most important assets providing food, fodder, fuel and fibre to its masses, which takes many thousands of years to build and very few to be wasted away[10]. History is replete with information about civilizations that have flourished and collapsed depending upon the productivity of their soils.

Soil: soul of infinite life

'*…(although) not an organism that can multiply, soil on the Earth is a living system.*'

– Hans Jenny

Though soil is of inert mineral origin by itself, it is a complex living environment. Microorganisms such as bacteria, fungi, protozoa, algae and virus and fauna such as earthworms, nematodes and insects bestow life to soil. A teaspoon full of soil contains more microorganisms than human population on Earth. Just 1 g of soil harbours several billion bacterial cells[11] and about 200 m of fungal hyphae[12], besides millions of actinomycetes, viruses and algae. Whitman *et al.*[13] reported that there are approximately 2.6×10^{30} total bacterial cells in the soil which comprise of a large portion of genetic diversity on the Earth. If we take the amount of DNA, 1 g dry soil contains around 1598 km long DNA from bacteria alone[14] having massive biochemical gene library producing diverse genetic instructions, present for almost 4 billion years on Earth[15]. The weight of these soil microorganisms, although microscopic, is substantial too. The biomass of bacteria and fungi in temperate grasslands has

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been estimated to be 1–2 and 2–5 t/ha respectively[16]. All these figures indicate that there are millions of unseen microscopic lives living beneath the Earth's surface.

Soil microbial activity: unseen so unknown

'*We know more about the movement of celestial bodies than about the soil underfoot.*'

– Leonardo da Vinci

What do the millions of microorganisms in the soil do? They perform a collection of life-supporting activities that play key roles in ecosystem processes[17,18]. The most important among them are: (i) Nutrient cycling – soil microbes drive the biogeochemical cycling of carbon, nitrogen, phosphorus, sulphur, etc. that circulate the life-building elements through the biological and physical phases on Earth. (ii) Organic matter decomposition and elemental transformation – the soil microorganisms decompose the organic material that is added to the soil and break down the complex chemical structure to its elemental form that supplies essential nutrients to the plants. (iii) Soil formation and structure – direct evidence through Mossbauer spectroscopy has shown that certain lithotrophic microbial community called Straub culture is able to weather rocks to soil[19]. Soil microbes produce mucilaginous chemicals that help in aggregate formation of soils[20,21]. (iv) Biotic and abiotic stress resistance to plants – there are several good reviews on the abilities of plant growth promoting rhizobacteria conferring resistance to plants against insect pests and fungal pathogens[22]. In coconut, root (wilt) diseased palms were observed to have lesser populations of plant-beneficial rhizobacteria compared to those palms that showed resistance[23]. Recent information highlights how these microbes help plants in keeping out fungal infection through physical barrier of closing the stomata pores[24]. Plants also enter into a special symbiotic relationship with soil microbes such as *Klebsiella pneumoniae* under drought situations[25], which drives developmental plasticity in plants in such a way that they promote lateral root and root hair development that can confer resistance to abiotic stress and prime the plant immune system[26]. (v) Supporting above-ground diversity – not only are soil microbiota the richest source of genetic diversity, it has also been estimated that about 20,000 plant species on Earth are completely dependent upon microbial symbionts for their growth and survival[27]. The soil biodiversity thus plays an essential role in the ecosystem services associated with soil processes that have been valued at US$ 90 trillion per annum globally[28]. The economic value of these ecosystem services carried out by soil microbes is estimated to be in the range US$ 25.60–425.50 $ha^{-1} yr^{-1}$ (mean US$ 160 $ha^{-1} yr^{-1}$) in organic fields and US$ 30.00–348.00 $ha^{-1} yr^{-1}$ (mean US$ 142 $ha^{-1} yr^{-1}$) in conventional ones[29]. Therefore, it is apt to declare that all organisms in the biosphere depend on microbial activity[30].

Microbes, the chemical engineers in soil, unlock the nutrients

'*The soil microbial biomass is the eye of the needle through which all natural organic matter that enters soil must pass as it is broken down to simple inorganic components that plants can use again*.'

– David S. Jenkinson

The soil microbial biomass, i.e. bacteria, actinomycetes and fungi, are the chemical engineers present in the soil that perform the key function of organic matter degradation. If it were not for them, the plant nutrients would remain locked away in the organic matter that is added to the soil. The processing of the soil organic matter (SOM) by the microbes yields two important products: essential nutrients for plant growth and humus, which is resistant to decomposition and helps sequester carbon in the soil. Half of the SOM is decomposed to its elemental form that supplies the essential plant nutrients, and the remaining fraction, known as humus, is stable and accumulates in the soil. In the process, respiration by the soil microbes evolves CO_2 that enters the Earth's atmosphere to be fixed as photosynthate by plants in the presence of light.

Not only does the microbial biomass process organic matter for the release of carbon and other important nutrients, it is also a storehouse of organic carbon and plant nutrients and can be easily estimated by chloroform fumigation extraction[31]. A collaborative research carried out in Germany and Sweden showed that microbial biomass plays a significant role in SOM genesis as 50% of the biomass-derived carbon remained in the soil after the turnover[32]. The interrelationship of plant inputs being converted to soil carbon through the activity of microbes has been proved empirically too in a recent publication[33]. The contribution to soil C and N at global level by microbial biomass was estimated to be 16.7 Pg C and 2.6 Pg N in the 0–30 cm soil profiles, and 23.2 Pg C and 3.7 Pg N in the 0–100 cm soil profiles[34].

Food for soil microbes

'*Life exists in the universe only because the carbon atom possesses certain exceptional properties.*'

– Sir James Jeans

All living organisms require energy for their survival, growth and normal activities. So too the soil microorganisms, even if their individual body size is microscopic. The energy is mainly obtained by the living organisms through consumption of food. What, therefore, is the food for the millions of microorganisms and metres of fungi that reside in the soils? It is carbon. Thus, carbon is the energy currency of the soil ecosystems, and microbial activity is governed by the availability of the fixed carbon present in soil[35]. Where from does the soil organic carbon (SOC) accumulate into the soil? It is derived from organic matter added to the soil through living organisms, about 85% from dead and decaying tissues of plants and animals, 10% from living roots and the remaining from soil organisms. The SOM is, therefore, one of the most critical components of soil habitat driving the crop production capacities of the soils and maintaining its fertility[36].

A hectare of healthy soil has microbial biomass equivalent to the weight of two adult cows, which has the capacity to process around 25,000 kg of organic matter annually in an area equalling a football field. This figure clearly indicates that the soil microbial community requires voluminous amount of food, i.e. organic carbon for its existence and life-giving activities. With the total live bacterial biomass alone estimated to be exceeding that of the plants and animals[37], supplying food to them is imperative for our survival since their functions drive the critical bio-geochemical cycles on which plants depend for their nutrition.

Soil organic carbon status

'*You will die but the carbon will not*.'

– Jacob Bronowski

A recent estimate using amended Harmonized World Soil Database pegs organic carbon stock in global soils at 0–100 cm depth to be 1417 Pg C (ref. 38). Estimates of SOC content in Indian soils were reported as early as in 1960 (ref. 39). Later, using ecosystem areas from different sources and representative global average C densities, organic C in Indian soils was estimated at 23.4–27.1 Pg (ref. 40). Gupta and Rao[41] reported an SOC stock in 48 soil series as 24.3 Pg. The recent estimate of SOC stock in Indian soils at 0–150 cm depth is 63 Pg (ref. 42).

The SOM is the second largest reservoir of carbon pool on the planet which contributes about 1500–1600 Gt of carbon. The rate of loss of carbon from the SOM to the atmospheric pool is 1–2 Gt each year. While 60 Gt of carbon per year entering the SOC sink as decaying biomass remains in the soil, about 61–62 Gt of carbon is lost from this pool as SOM is oxidized by the atmosphere. Thus, the annual loss of carbon from the SOM pool to the atmosphere is outstripping the amount of carbon that is being added from above ground to the SOM (http://soilcarboncenter.k-state.edu/carbcycle.html).

In India, in the areas where agriculture is being done in an intensive manner and forest areas are getting cleared for agriculture, SOC content has decreased. One of the main factors responsible for the decline in SOC content, besides soil erosion and fossil fuel exploitation, has been the agriculture systems worldwide, which have partially or completely removed the above-ground biomass as feed, fodder, bedding, fuel and building material to satisfy the food, fodder, shelter and clothing needs of humans and animals. This decline in SOC and its quality has a harmful impact on soil biodiversity and soil health and fertility[43]. The sum total effect on soil is double negative pressure: more demand for crop production and drastic cut in return of organic matter to soil. The effect of SOC loss in Indian soils is highlighted by Maheswarappa *et al.*[44], who report that though there has been steady increase in food production from 1970 to 2009, the fertilizer use efficiency had decreased drastically requiring more C-inputs to be added each passing year to produce the same per unit C-output. This, they mention, is the result of acute decrease in C-sustainability index of Indian soils from 7 during 1970 to 3 by 2009. Without organic inputs, mineral fertilizers are reported to worsen soil conditions[45].

Returning carbon to soil

'*Nothing can be created from nothing*.'

– Lucretius

During the carbon cycle, CO_2 in the atmosphere is converted to complex sugar molecules in plants through photosynthesis, which are then consumed and assimilated by microorganisms, upon addition to the soil, and then released again as CO_2 to atmosphere through respiration and decomposition of the added tissues as well as combustion of fossil fuels. For agricultural production, non-return or diminished return of organic matter and residues is serious as it deprives the soil biota of its food, which results in reduced organic carbon accumulation and reduced nutrient availability to plants causing loss of the soil biodiversity attendant with loss of soil health and fertility[39,46].

It is highly appropriate, even after the passage of seven decades, to consider Sir Albert Howard's[47] suggestion of 'Law of return' advocating recycling of organic waste material to build and maintain soil fertility and humus content. Howard's concept of soil fertility was centred on building soil humus, with an emphasis on a 'living bridge' between soil life, such as mycorrhizae and bacteria, and how this chain of life from the soil supported the health of crops, livestock and mankind. Unfortunately, the 'Law of return' has been ignored in the Indian agricultural scenario resulting in significant decrease in SOM, and consequently SOC, in many of the cropped soils. Lal[48] opined that increase of the SOC pool in the root zone by 1 Mg C ha^{-1} yr^{-1} can cause increase in grain yield (kg ha^{-1} Mg^{-1} C) of food crops in a developing country by 200 to 300 for maize, 20 to 40 for wheat, 20 to for rice, 80 to 140 for sorghum, 30 to 70 for millet [*Pennisetum glaucum* (L.) R. Br.], 30 to 60 for bean

(*Phaseolus vulgaris* L.) and 20 to 50 for soybeans. One of the methods of increasing carbon content in soil is through addition of agricultural wastes produced in large quantities in India. Addition of agro-wastes also satisfies the 'Law of return' concept propounded by Howard[47].

Crop-residue availability in India

The Ministry of New and Renewable Energy, Government of India (MNRE, 2009) reports that 500 million tonnes of crop residues are generated every year in the country. This figure could be higher considering the record agricultural production being achieved in the last couple of years in India. A large amount of these agro-wastes find use as animal feed, fuel and home construction material in rural areas, soil mulch and manure in farming. Yet, 84–141 million tonnes yr^{-1} of these residues, a substantial amount, remains unutilized and burnt-off in the farm (MNRE, 2009). More accurate assessment pegs the unutilized crop-residues burnt on-farm to 90 million tonnes yr^{-1} (ref. 49).

Ninety million tonnes of invaluable carbon is burnt that could be a significant source of food to the microbes, if added to soil, where intensive agriculture is carried out in several parts of our country. This will significantly help in augmenting the nutrient and carbon reservoir in soils and reduce the addition of external nutrient sources in agriculture. It will also reduce the addition of greenhouse gas into the atmosphere[49]. With land area available per person shrinking quickly in India, adoption of the 'Law of return', becomes critical to sustain food production and nutrition security of our nation. A recent policy paper from the National Academy of Agricultural Sciences (NAAS)[50] discusses several important strategies of utilizing the crop-residues and returning the much needed carbon to soils.

The Central Plantation Crops Research Institute, Kasaragod, whose mandate crops are coconut, areca nut and cocoa, has been striving to develop feasible technologies that satisfy the 'Law of return'. Recycling of coconut[51,52], areca nut and cocoa[53] wastes to vermicompost and vermiwash[54], coir pith to compost using poultry manure[55] and immature coconut husks (waste generated by tendernut parlours) to biochar (Gopal *et al.*, unpublished) address the issue of providing food to soil microbes. The benefit of such technologies can be realized when adopted and applied on a large scale.

Humus to human to humus

'*...the Latin name for man, homo, derived from humus, the stuff of life in the soil.*'

– Daniel Hillel

All lives, plants, animals and humans, are made of carbon. All life-giving carbon is derived from SOM (humus) present in the soil. All humus is produced from plant and animal matter added to soil by the action of microorganisms. In fact, microorganisms are becoming central to all life. Metagenomic studies using next-generation sequencing technologies in the human gut microbiome project[56] have revealed that there are 100 trillion bacteria in the human body, particularly inside the gut, and they outnumber our own cells 10 to 1, disclosing a complex interaction of worlds within worlds[57]. These studies are leading to the argument that microbes are in charge of our lives[58]. Recent research publications reporting gut microbiome as a key factor for proper brain development[59], overcoming gastro-intestinal disease[60], control host appetite[61] add to the fact that microorganisms are indeed controlling our lives. And there appears to be significant body of research to prove that rhizosphere microbiota control plant health too[62], bringing forth an article on the analogy of gut and root microbiota[63].

Dove[64] mentions how microbial research using improved microscopes in the 19th century proved an absurd theory: that diseases were caused not by poor hygiene and foul vapours, as everyone knew they were, but by organisms too small to see with the naked eye. Now in the 21st century, next-generation sequencing technologies and bioinformatics are slowly proving true another more absurd theory: that humans and other macroorganisms are not individual entities, as everyone knows they are, but complete ecosystems dependent on billions of microbes. Supplying food to the microbes is therefore supplying food to us. Let us begin with the soils.

'Soil is the stomach of plants' according to the eminent agricultural scientist Swaminathan[65], teeming with millions of hungry microbes which must be fed first in order to feed the plants and other lives. Let us focus on feeding the microbes in the soil. Mahatma Gandhi's quotation 'To forget how to dig the Earth and to tend the soil is to forget ourselves', should be the driver to attain this goal.

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