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A Diagrammatic Mini-Review on the Soil-Human Health-Nexus with a Focus on Soil Microbes

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RECOGNITION of the links between soil and human health goes back thousands of years, when ancient people recognized the value of soil and its potential for human life. As a dynamic, complex, and open system soil consists of flora and fauna (microbes and others), water, air, and mineral and organic particles. These components of soil may cause negative (diseases, nutrient imbalances) and/or positive (supply of antibiotics, bioactives, secondary metabolites, or essential nutrients) impacts on human health. Soil microbes are a crucial component of the soil system that can cause human diseases or be used in the production of antibiotics and other drugs. There is still great need to study the soil microbial community, as new soil microbes are regularly discovered along with new compounds that are beneficial to human health, such as drugs, bioactives, and secondary metabolites. This mini-review discuses the potential of soil microbes, including their positive and negative influences within the soil-human health nexus. This work is unique in that it mainly depends on diagrammatic presentations, which can explain the target meaning in a very simple manner.

Keywords: Soil-water nexus, Microbiota, Microflora, Rhizosphere, Antibiotics.

1. Introduction

"*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 1938; cited from van Elsas et al. 2019). Soil is teeming with millions of organisms, which makes it a living and dynamic system (**Fig 1)**. Humans cannot live without soil because it is a major supplier of food, fiber, fuel, and other human necessities (El-Ramady et al. 2022a). Thus, it is very important to sustain and conserve soils through the preservation of soil fertility and its diverse ecosystems. There is a long history of recognizing the links between soil and human health, including (1) the soil–plant/animal–food system is the main source of essential nutrients in the human diet, (2) soil is a crucial part of food security, (3) soil may cause human health problems through exposure to pollutants and pathogens, nutrient imbalances, etc., (4) soil can provide medications like antibiotics and cancer fighting drugs, and (5) soil is an essential component in water

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purification (Brevik and Sauer 2015; Oliver and Brevik 2022). Soil also can impact human health through its inhalation, ingestion, or through skin lesions. Through these direct and/or indirect connections harmful substances may pass into the human body, including heavy metals, organic pollutants, radionuclides, and microorganisms (Oliver and Brevik 2022).

The soil-human health-nexus is basically built on the premise that "*the health of soil, plants, animals, people, and the environment is one and indivisible*", as proposed by Sir Albert Howard (1920) and supported by Lal (2021). Soil microbes are a major component of soil that can play a great role in determining soil health or quality (Seitz et al. 2021). Several publications have reported on soil microbes and their relationship to human health (Ochoa-Hueso 2017; Nieder et al. 2018; Meena 2018; van Elsas et al. 2019; Blum et al. 2019; Tate 2021; Das et al. 2022). Many publications have also discussed the broader relationships between soil and human health, including soil microbes, such as Brevik et al. (2022), El-Ramady et al. (2022b), Oliver and Brevik (2022), and Rekik and van Es (2022).

Therefore, this review highlights the soil-human health nexus with a focus on soil microbes using a diagrammatic presentation. Topics include soil microbes as both a source of human diseases and as a positive influence on human health, as well research priorities.

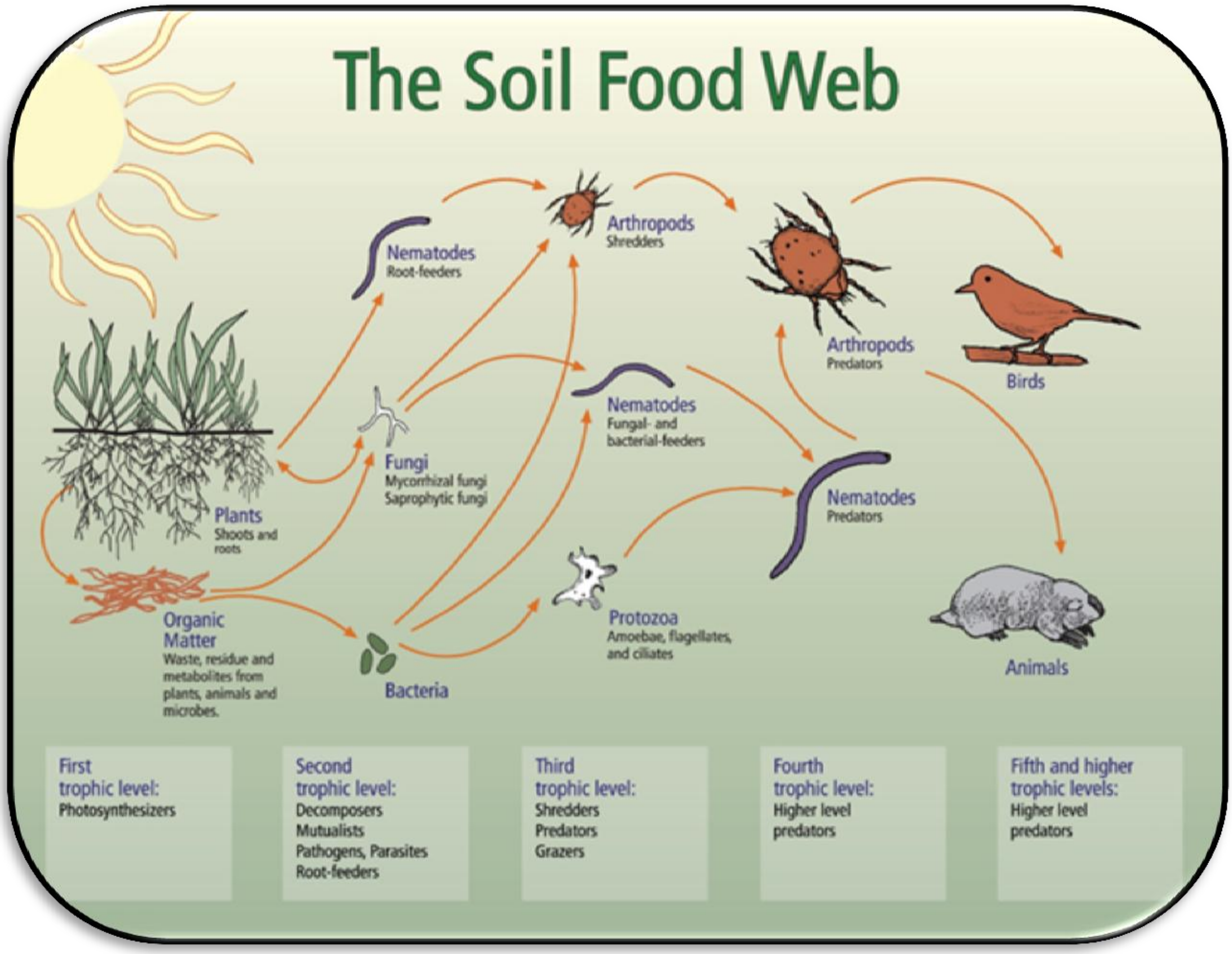

Fig. 1. The soil system is teeming with life, forming a complex and interconnected ecosystem. This life, in turn, can have profound influences on human health. Image courtesy of USDA-NRCS.

2. Soil microbes: An Overview

The soil is a diverse ecosystem, in which millions of soil flora (plant kingdom) and fauna (animal kingdom) live. These organisms include macro- and micro- flora (plant roots, macro-algae, bacteria, actinomycetes, fungi, etc.), and fauna (protozoa, nematodes, earthworms, termites, ants, grubs, etc.). Figure (1) shows some of the living relationships found in the soil system. Beneficial soil microbes may include plant growth-promoting rhizobacteria

(PGPR) and bacteria (PGPB); additional research should focus on how to maximize the benefits from these organisms. Potential applications include using PGPR and PGPB as biofertilizers, biopesticides, and biocontrol agents instead of using chemical fertilizers to enhance crop productivity (Das et al. 2022). Soil microbes can improve soil fertility by breaking down soil organic matter, recycling nutrients in the soil, and fixing nitrogen. They can also promote plant growth by controlling pests and diseases as biocontrol agents, forming soil humus, and enhancing soil structure. Several books have been published that provide more information about soil microbes (e.g., Meena 2018; van Elsas et al. 2019; Tate 2021). The seven most important questions regarding soil life are presented in Fig. (2).

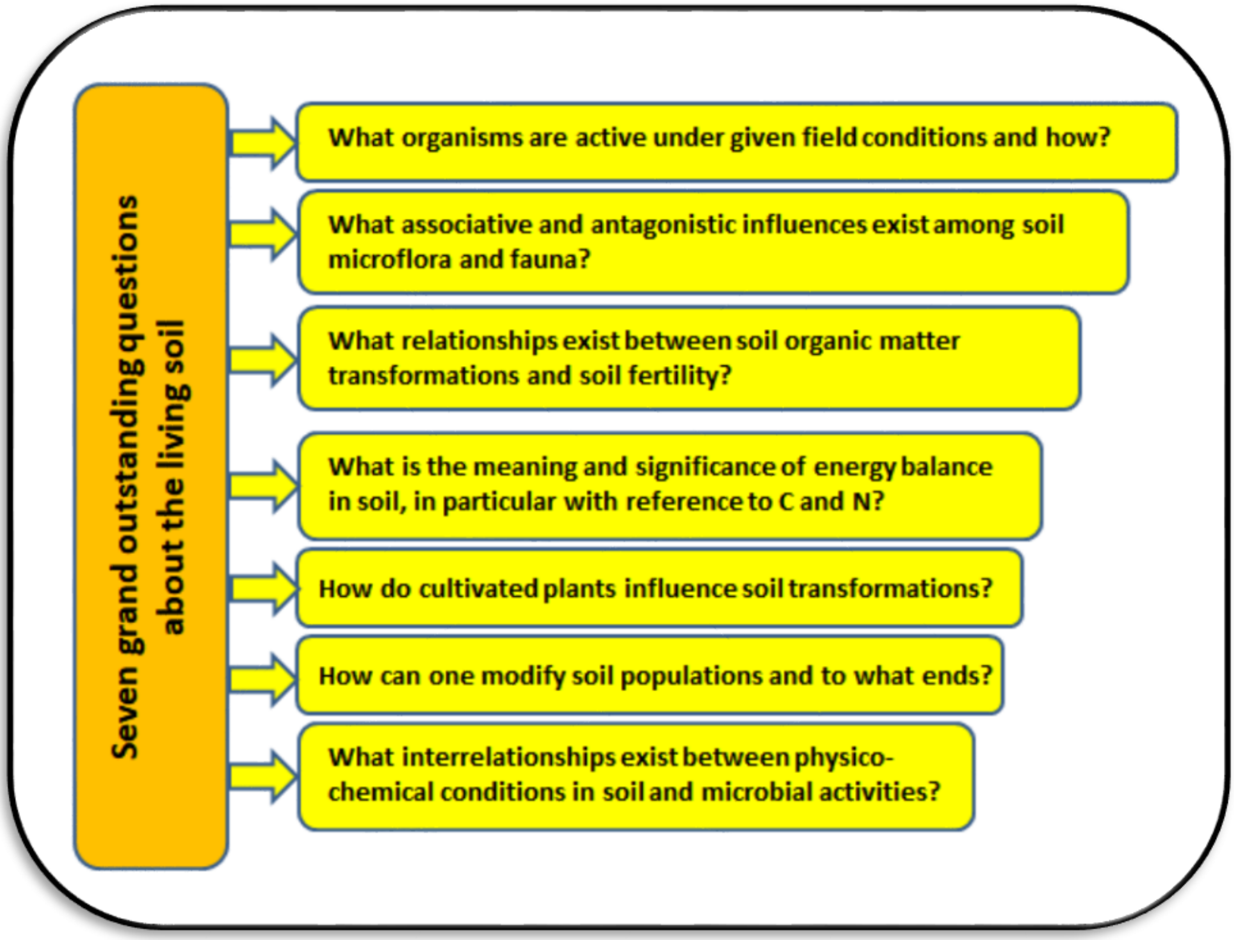

Fig. 2. Several years ago, several questions concerning the living soil were asked by scientists. These are considered outstanding questions (adapted from van Elsas and Nannipieri 2019).

Soil microbes are very small organisms. Their size is a distinguished feature that gives them the ability to have both positive and negative impacts on human health (Table 1; Fig. 3). One gram of soil can contain billions of soil microbes (Trevors, 2010). Soil pores may be occupied by water, air, or soil microbes. The physical niches inhabited by soil microbes will mainly be soil pore walls, but soil water in the pore channels may contain and transport significant numbers of freely mobile bacteria (Table 1). To understand how we can manage soils for health and sustainability to enhance the soil-food-environment-health nexus, it is very important to study the crucial functions of soil microorganisms (Fig. 4). These functions drive most of the relevant biogeochemical processes that occur in soil (van Elsas and Nannipieri 2019).

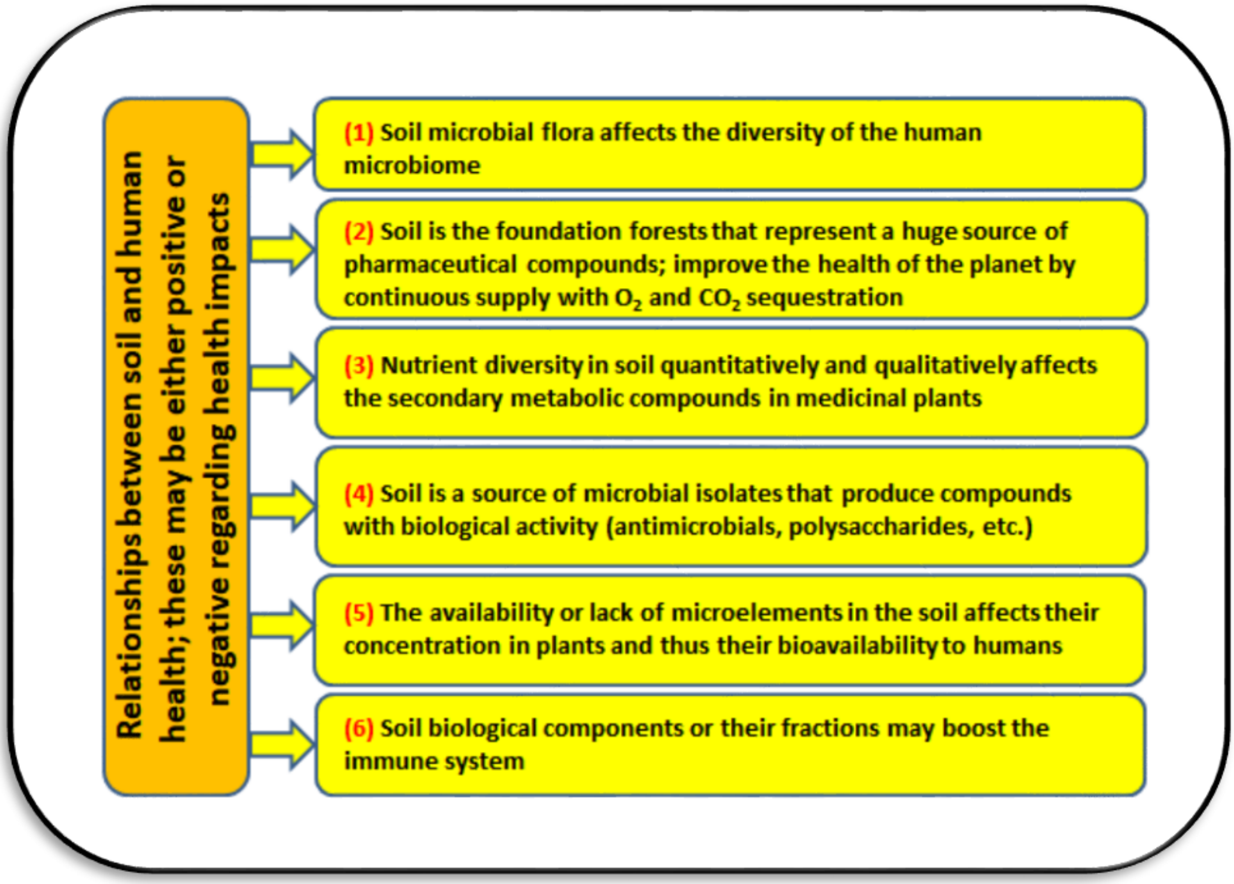

Fig. 3. Soil microbes are distinguished by their small size, which gives them the ability to have many positive and negative impacts on human health.

Table 1. Approximate dimensions (µm) of soil particles and biota comparing to water-filled pores and water films (adapted from (van Elsas 2019).

Soil item	Type	Approximate dimension (µm)
Soil particles	Stones	>2,000
	Coarse sand	2,000–200
	Fine sand	200–50
	Silt	50–2
	Clay	2–0.2
Plant materials	Roots	1,000
	Fine roots	1,000–50
	Root hairs	15–7
Microbes	Fungal hyphae	10–3
	Actinomycetes	1.5–1.0
	Bacteria	0.5–1.0
	Viruses	0.05–0.2
Some soil animals	Earthworms	5,000–2
	Mites	2,000–500
	Nematodes	2,000–500
	Protozoa	80–10
Water-filled pores	−10 kPa	<30
	−100 kPa	<3
	−1,000 kPa	0.3
Water films	−100kPa	<0.0003
	−1,000kPa	Few molecules thick

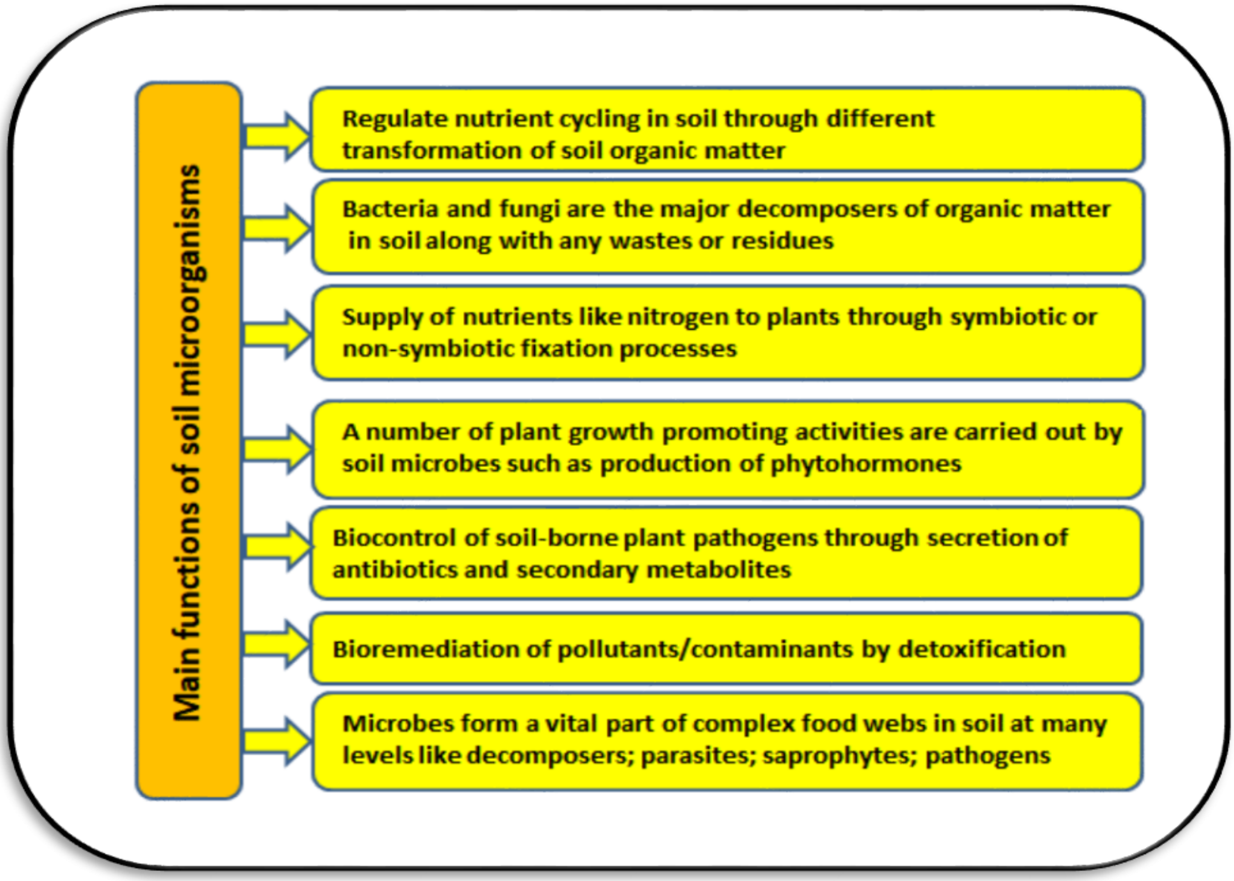

Fig. 4. The main functions of soil microflora.

3. Soil microbes as a source for human diseases

The history of soil microbiology goes back to the creation of modern soil science as an independent scientific discipline (Brevik and Hartemink, 2010) and the field has evolved ever since (**Fig. 5**). Several soil microbes have negative effects on human health (i.e., cause human diseases) through natural or anthropogenic pathways. This impact may be due to direct exposure to soils or soil components, primarily *via* ingestion, inhalation, or dermal absorption/penetration, or through indirect pathways such as beneficial microbes enhancing plant growth or suppressing pathogenic microbes (Brevik et al. 2020). A few common human pathogens found in soil are listed in **Table 2**.

Table 2. The negative impact of some soil organisms on human health on the global level (adapted from Olivera and Brevik 2022).

Organism	Common name	Point of infection/ gateway	Disease name	Soil residency
Entamoeba histolytica		Intestine	Amebiasis	Incidental
Giardia lamblia	Giardia	Large intestine	Giardiasis	Transient-incidental
Dientamoeba fragilis	Gastrointestinal tract	*D. fragilis* infection		Unknown
Aspergillus sp.		Respiratory	Aspergillosis	Permanent
Trichophyton sp., *Microsporum* sp., *Epidermophyton* sp.	Ringworm	Skin contact	Tinea corporis	Common
Clostridium tetani		Skin trauma	Tetanus (Lockjaw)	Permanent
Escherichia coli	*E. coli*	Ingestion	Diarrhea	Incidental
Clostridium botulinum		Ingestion	Botulism	Permanent
Clostridium sp.		Skin trauma	Gas gangrene	Permanent
Rickettsia sp.		Tick bite	Rocky Mountain spotted fever	Periodic

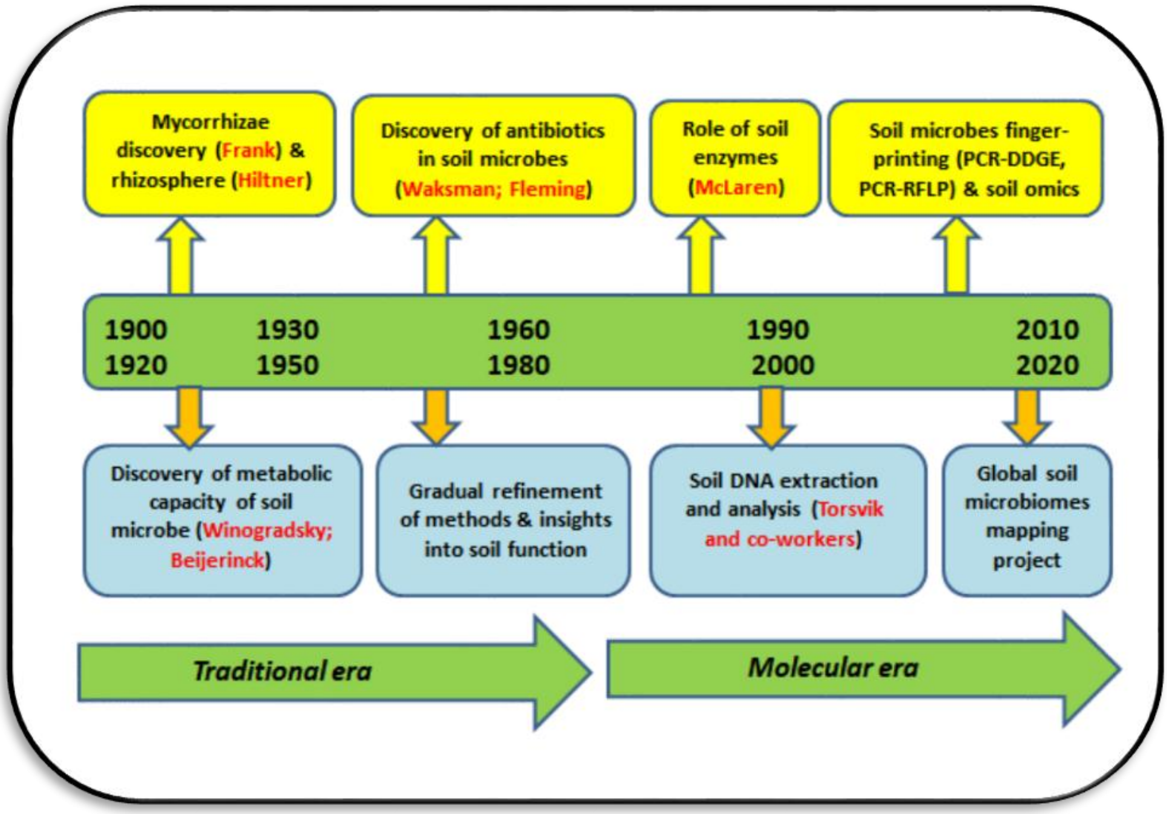

Fig. 5. Soil microbiology has a history of more than 100 years of research. Its development can be divided into several periods, i.e., early microbiology or the traditional era (in which Winogradsky, Beijerinck and Waksman played pivotal roles) to the era typified by McLaren, or soil biochemistry and processes, to the molecular era (adapted from van Elsas and Nannipieri 2019).

Ingestion of pathogenic soil microbes can cause human diseases such as:

1- Xenobiotic exposure: this exposure may cause cancer, obesity/metabolic disease, or reproductive, developmental, and cognitive anomalies,

2- Gastroenteritis diarrheal disease caused by ingestion of small quantities of soil contaminated with enteric bacterial pathogens (Campylobacter, Escherichia coli, Shigella spp.), viruses (Norwalk virus), or protozoans (Cryptosporidium parvum), and

3- Helminthiasis: parasitic intestinal infection caused by ingestion of soil containing Ascaris or whipworm eggs (Brevik et al 2020).

4. Beneficial soil microbes for human health

Soil microbes have several direct and/or indirect benefits to human health. Some soil microbes possess multifaceted plant growth–promoting traits. Thus, the interaction between soil microbes and cultivated plants have attracted worldwide attention due to the need to produce enough nutritious food for global needs and restore and maintain soil biodiversity, which represents a priority issue in many conservation policies. Soil microbiota has been often investigated for its critical roles in soil sustainability and functioning. Similarly, the soil microbial community plays a crucial role in maintaining soil health, including the capacity to control diseases caused by soil-borne pathogens (**Fig. 6;** Jayaraman et al. 2021). Additional benefits of soil microbes that are useful for human health include:

1- Soil microbes for bio-decomposition of organic wastes/residues to increase nutrient bioavailability for cultivated plants (Lou et al. 2022),

2- Using antagonistic soil microbes against phytopathogens such as bacterial leaf and fungal sheath blight diseases in rice (Kannan et al. 2021),

3- Beneficial soil microbes for N-fixation, like legume symbioses for plant production (Udvardi et al. 2021),

4- Biodegradation and decontamination of pollutants by soil microbes (Li et al. 2022),

5- Production of bioactive compounds by soil microbes (Haruna and Yahaya 2021),

7- Production of secondary metabolites by soil microbes (Mahmood et al. 2022),
8- Soil microbes as a source of antibiotics and other pharmaceuticals (Alvarado et al. 2020; Suman et al. 2022), and,
9- Provision of a myriad of key ecosystem services (ES), including (*i*) provisioning services or products that soil ES make available for human use, (*ii*) regulating services by mediation/moderation of the environment in ways that affect health, safety, and comfort through food and fiber production, building materials, biorepository, climate and water regulation, and (iii) cultural services that affect the physical and mental states of people (Brevik et al. 2020).

Important interactions in the plant-soil-microbes system that support nutrient acquisition for better plant growth through sustainable agricultural practices, and through that human health, are shown in **Fig. 7**. Plant growth-promoting microbes can provide resistance against phytopathogens *via* the production of phytohormones and regulating nutritional balances in unfavorable stress conditions. Thus, plant-soil-microbes create a tripartite interaction environment that is controlled by the dominant interaction, such as plant-microbes, microbes-microbes, and microbes-plant interactions (Das et al. 2022). The impact of soil microbes on human health can draw on the **Fig. 8.**

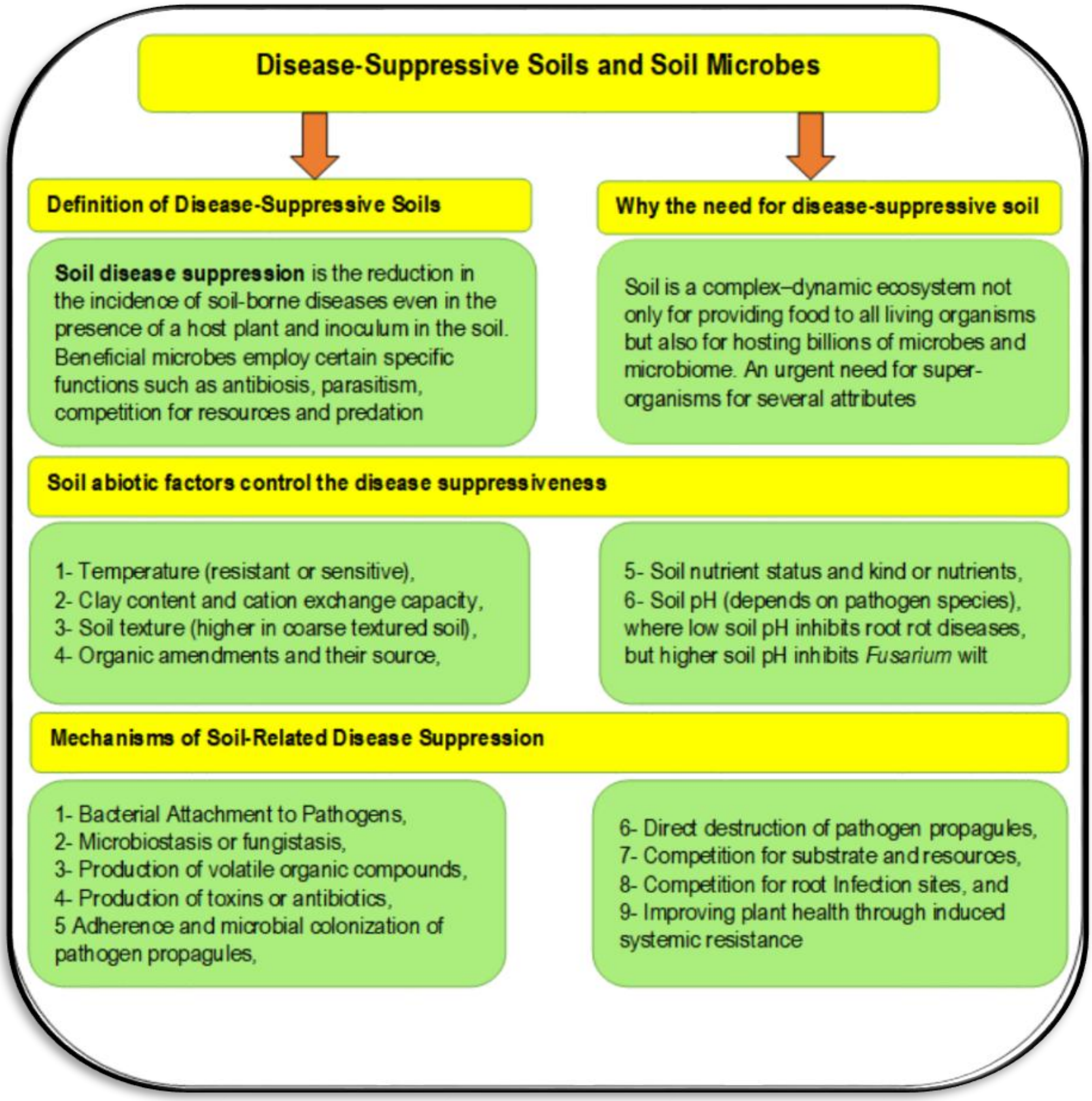

Fig. 6. Disease-suppressive soils by soil microbes and mode of action (Source: Jayaraman et al. 2021).

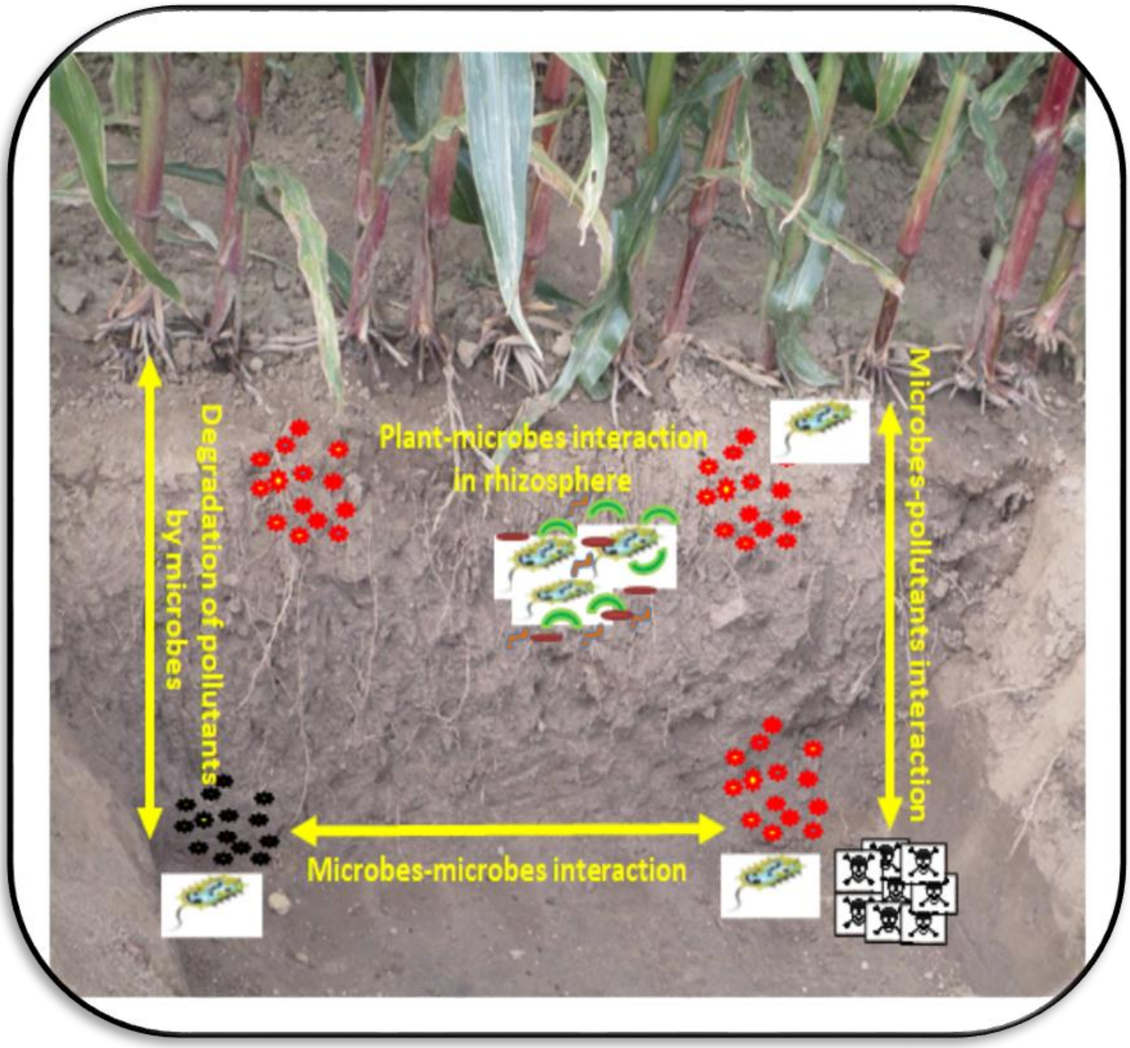

Fig. 7. The soil microbes-plant interaction, which controls biogeochemical cycles in the soil through uptake, decomposition, or degradation of soil organics. The interactions may be influenced by signals such as carbon fluxes, phenolic acids, flavonoids, organic acids, NO, H_2O_2, etc. Microbe-microbe interactions are influenced by signals like indole, antibiotics, auto inducer 2, etc. Microbes to plant signals may include auxins, N-acyl-L-homoserine lactones, volatile organic compounds, and other plant hormones (adapted from Das et al. 2022).

5. Conclusions and researchable priorities

Soil can impact humans and their health through the direct or indirect and negative or positive ways. Soil microbes are important to this relationship, and more research in this area is needed to better understand how soil microbes influence human health and how agricultural management influences the soil microbial community. Lal (2021) summarized research needs in this area as:

(1) What are the soil and crop-specific mechanisms that can induce disease suppression in soils?

(2) Which agricultural management practices can enhance general and specific disease suppression?

(3) Which properties of compost or organic amendments should be assessed to strengthen disease suppression?

(4) How can microbiome research help us understand the mechanisms of general and specific disease suppression?

(5) Can the cause–effect relationship between soil health and human health be established through nutritional quality of the food produced?

(6) What are the main determinants of soil biodiversity and how they affect disease suppressiveness and human health?

(7) How do the positive effects of soil structure, aeration and porosity influence disease suppression?

(9) Which soil physical attributes are linked to microbial community structure and their impacts in soil?

(10) How can we enhance the soil–plant–animal–human health nexus and encourage use of these methods?

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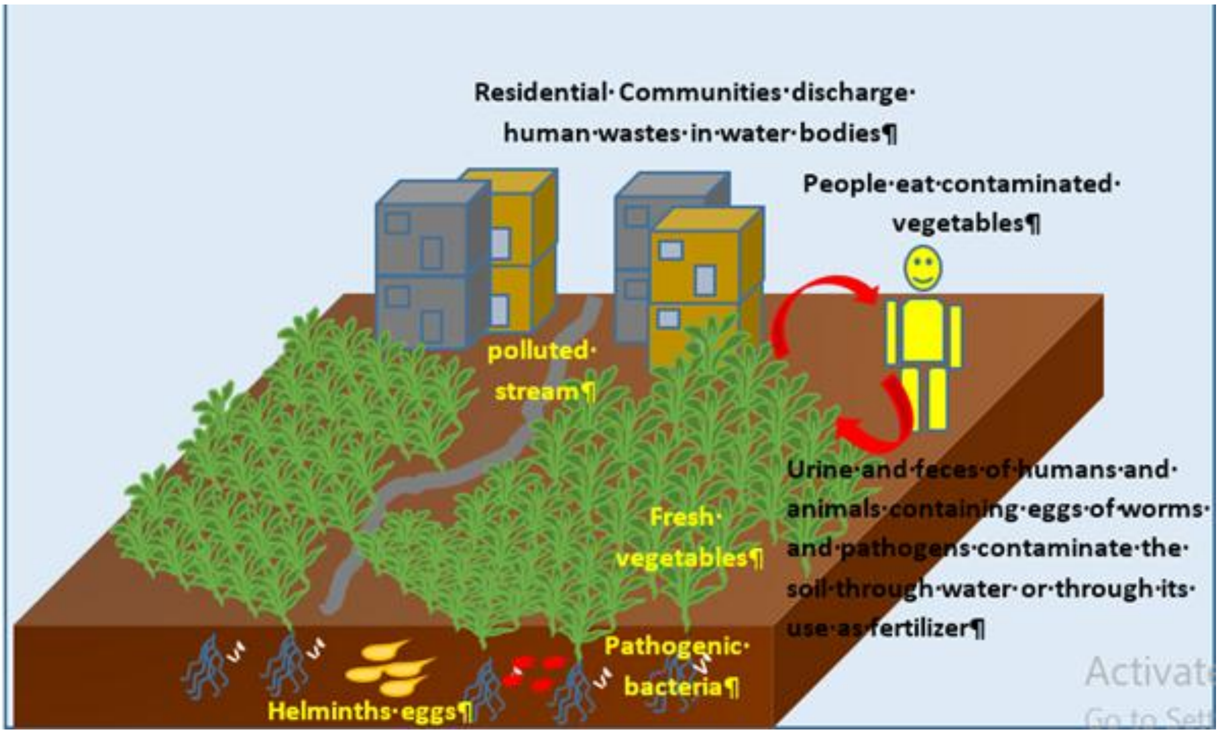

Fig 8. Soil-transmitted helminths such as *Ascaris lumbricoides*, whipworm (*Trichuris trichiura*), and hookworm (*Ancylostoma duodenale* and *Necator americanus*). And microbial pathogens such as Salmonella enterica, Campylobacter spp., Escherichia coli (food-born gastrointestinal disease), Legionella spp. (pneumonia; Legionnaires' Disease), Mycobacterium leprae (leprosy), *Shigella* spp.

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