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SOIL AND HUMAN HEALTH RELATIONSHIP: EXPLORING THE INTERCONNECTEDNESS OF ECOSYSTEM AND WELL-BEING – A REVIEW

AUTHORS:
S. N. Obasi[1*], V. A. Tenebe[1], C. C. Obasi[2], D. N. Osujieke[3], and P. E. Imadojemu[3]

AFFILIATIONS:
[1] Department of Crop and Soil Sciences, Faculty of Agricultural Sciences, National Open University of Nigeria, Kaduna Campus, Nigeria
[2] Department of Crop Science and Horticulture, Nnamdi Azikiwe University, Awka, Nigeria
[3] Department of Soil Science and Land Resources Management, Federal University Wukari, Taraba State Nigeria

***CORRESPONDING AUTHOR:**
Email: nobasi@noun.edu.ng

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Abstract

This review examines the intricate connections between soil health and human well-being, highlighting both the benefits of healthy soils and the risks posed by soil contamination and degradation. A comprehensive literature review was conducted by synthesizing peer-reviewed articles, reports, and case studies published between 2000 and 2024, with earlier seminal works included where relevant. Sources were retrieved from databases such as Scopus, Web of Science, PubMed, and Google Scholar using keywords including soil health, human health, soil contamination, food security, and ecosystem services. The selected literature was thematically analyzed to identify ecological, nutritional, biomedical, and policy dimensions of the soil–human health nexus. The review reveals that healthy soils are fundamental to food security, nutrition, disease prevention, and ecosystem stability. Conversely, degraded or contaminated soils contribute to micronutrient deficiencies, exposure to toxic substances, and the spread of soil-borne diseases. Case studies further illustrate the long-term health risks associated with pollutants such as heavy metals and persistent organic chemicals. The review also highlights emerging evidence of soil's role in mental health and its potential for disease prevention through soil-derived compounds and beneficial microorganisms. The findings emphasize the urgent need for integrated policies and sustainable soil management practices that address both agricultural productivity and public health. Strengthening soil conservation, remediation, and monitoring strategies will be critical in reducing health risks and ensuring resilient food systems. The review calls for interdisciplinary collaboration among soil scientists, public health experts, and policymakers to safeguard human health and the environment through the protection of soil resources.

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1.0 INTRODUCTION

Beyond its ecological importance, soil is intricately connected to human health [1]. It sustains food systems, influences nutritional quality, and acts as both a source of essential nutrients and a potential reservoir of harmful contaminants. This broader view establishes the foundation for understanding soil as a determinant of human well-being [2]. The state of the soil directly and significantly affects human health, from supplying vital nutrients for the food chain to serving as a holding ground for dangerous viruses and poisonous substances [3], [4].

Human health and soil have a complicated and wide-ranging relationship. Growing nutrient-dense crops, which are the foundation of a balanced diet and aid in the prevention of disease and malnutrition, requires fertile, healthy soils [5]. In contrast, contaminated or degraded soils can cause serious health problems, particularly for vulnerable populations, by compromising food security, exposing communities to harmful substances, and promoting the spread of soil-borne illnesses [6]. In addition to influencing agricultural production, the physical, chemical, and biological properties of soil also impact the availability of vital nutrients like iron, zinc, and iodine, which further shapes human nutrition and health outcomes [7].

This article explores the complex relationship between soil health and human well-being, focusing on both the benefits of maintaining healthy soils and the risks posed by soil contamination and degradation. It highlights how important soil quality is to preserving both individual and community health by looking at processes including nutrient cycling, pollutant exposure, and disease transmission [8]. A multidisciplinary strategy combining soil scientists, public health specialists, and policymakers is advocated in the discussion, which also highlights methods to improve soil quality, avoid contamination, and advance public health [9].

In an era of increasing soil degradation driven by unsustainable agricultural practices, industrial pollution, and climate change, understanding the soil-human health nexus has never been more urgent [8], [10]. This article emphasizes the importance of sustainable soil management as a cornerstone for safeguarding both food security and public health, while advocating for comprehensive policies and initiatives aimed at restoring and preserving this critical resource [11].

2.0 METHODS OF LITERATURE SEARCH AND SELECTION

This review employed a systematic and integrative approach to explore the relationship between soil health and human well-being. The methodology involved four main stages: literature identification, screening and selection, data extraction, and thematic synthesis.

2.1 Literature Search Strategy

A comprehensive literature search was conducted between January and March 2024 across major scientific databases including *Scopus*, *Web of Science*, *PubMed*, and *Google Scholar*. Supplementary searches were also performed through institutional repositories, reference lists of key publications, and grey literature (e.g., FAO and WHO reports). The search combined relevant keywords and Boolean operators such as **"soil health" AND "human health"**, **"soil contamination" OR "pollution"**, **"ecosystem services"**, **"food security"**, and **"soil-borne diseases"**. The search was limited to English-language publications from **2000 to 2024**, though seminal studies published before 2000 were included when foundational to the topic.

2.2 Inclusion and Exclusion Criteria

Articles were included if they: Examined direct or indirect relationships between soil quality and human health; Addressed soil contamination, nutrient cycling, or soil-borne diseases; Discussed ecosystem services linking soil and human well-being; or Presented policy, management, or technological interventions relevant to soil–health interactions. Excluded materials were those focusing solely on agronomic yield without human health implications, articles lacking empirical or conceptual grounding, or studies with inaccessible full texts.

2.3 Screening and Quality Control

All retrieved publications were screened in three stages. Titles and abstracts were first reviewed for relevance, followed by full-text examination. Duplicates were removed using *Zotero* and *EndNote* reference management software. To ensure quality and credibility, only peer-reviewed journal articles, institutional reports, and reputable conference papers were included. The *Critical Appraisal Skills Programme (CASP)* checklist was adapted to assess methodological soundness, clarity of objectives, and validity of conclusions.

2.4 Data Extraction and Analysis

Data from eligible studies were extracted using a standardized form capturing the following variables: author(s), year, study location, focus area (e.g., soil contamination, nutrient cycling, microbial diversity), methodology, and key findings related to human health. Extracted data were coded and grouped thematically under four domains: (i) ecological and ecosystem services, (ii) nutritional and biomedical links, (iii) soil contamination and health risks, and (iv) policy and management responses.

2.5 Thematic Synthesis

A narrative and thematic synthesis approach was used to integrate findings from diverse sources. Themes were compared across geographical regions to identify patterns, knowledge gaps, and emerging

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trends. The synthesis emphasized causal pathways connecting soil health to food quality, disease prevalence, and environmental sustainability.

2.6 Limitations of the Review

This review is limited by its dependence on published literature available in English and potential publication bias favoring studies with positive or significant findings. Nonetheless, the diverse range of sources and multidisciplinary perspectives provide a robust understanding of the soil–human health nexus. This structured approach ensured that the review was comprehensive, transparent, and reproducible, thereby providing a credible synthesis of existing evidence on how soil health influences human well-being.

3.0 SOIL HEALTH AND ITS COMPONENTS

The continuous capacity of soil to sustain plants, animals, and people as a dynamic living ecosystem is known as soil health [10], [12]. It is essential for conserving biodiversity, regulating climate, guaranteeing clean water, and promoting crop growth [13]. In addition to discussing the physical, chemical, and biological aspects of soil health, this section explores the vital ecosystem services that healthy soils provide.

3.1 Soil Properties

3.1.1 Soil physical properties

Supporting plant growth and providing vital ecosystem functions depend heavily on the physical makeup of the soil [1], [14]. The organization of soil particles, such as clay, silt, and sand, into aggregates is referred to as soil structure. Air circulation, water infiltration, and root penetration are all improved by well-aggregated soil and are essential for the proper growth of plants [2], [15]. Furthermore, a well-structured soil helps avoid compaction and erosion, which can otherwise lower crop output. The relative amounts of sand, silt, and clay in the soil form its texture, which has a major impact on its characteristics [16]. While clay-rich soils are fine-textured and retain more water, they may also limit root growth and water circulation [17]. Sandy soils are coarse and drain rapidly. Because of its optimum drainage and water retention qualities, loam—a balanced mixture of sand, silt, and clay—is frequently regarded as the best soil for plant growth [2], [18].

Another important component of soil fertility is its ability to retain water. More water can be held by soils with a well-developed structure and a high organic matter content, giving plants a consistent supply during dry spells. Conversely, inadequate soil structure can result in drought stress or waterlogging, both of which can impair plant productivity and health [19].

3.1.2 Soil chemical properties

Because they affect the availability of nutrients necessary for plant growth, the chemical characteristics of soil are vital to its fertility [20]. Important macronutrients like potassium, phosphorus, and nitrogen as well as micronutrients like iron, zinc, and manganese are found in soils and are needed by plants in different proportions. Although micronutrients are necessary in trace levels for proper plant development, macronutrients are needed in greater proportions [14]. Healthy soil is characterized by a balanced supply of nutrients, which promotes the best possible plant growth. On the other hand, imbalances like too much phosphorus or too little nitrogen can impede plant growth and lower agricultural yields [21]. Microbial activity and nutrient availability are also significantly influenced by the pH of the soil. The pH range of 6.0 to 7.5 is ideal for the majority of plants [22]. Extremes in soil pH can negatively impact plant health by restricting nutrient availability. For instance, highly acidic soils can lead to aluminum toxicity, which stunts root growth, while highly alkaline soils may immobilize nutrients like iron and manganese, causing deficiencies [23]. Maintaining the appropriate chemical balance in soil is therefore essential for sustainable agricultural productivity.

3.1.3 Soil biological properties

Life abounds in soil, and its biological characteristics are essential to its fertility and general health. In order to break down organic matter, cycle nutrients, and promote plant growth, microorganisms including bacteria, fungus, and other soil-dwelling creatures are essential [24]. For instance, mycorrhizal fungi improve nutrient uptake by expanding the reach of plant root systems, while nitrogen-fixing bacteria transform atmospheric nitrogen into forms that plants can use [25]. A varied and vibrant microbial community, which drives nutrient cycling and fosters strong plant health, is a hallmark of healthy soil. Plant waste, animal feces, and decomposing microorganisms are sources of organic matter, which helps to improve soil structure, improve water retention, and provide nutrients to soil organisms [26]. Additionally, it serves as a carbon reservoir,

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boosting soil fertility and resilience to environmental challenges like drought and compaction [27].

Figure 1 illustrates the interconnected relationship between soil health, human well-being, and the broader environment. Healthy soils support nutrient-rich crops, safe water, and resilient ecosystems, which in turn contribute directly to improved human nutrition, reduced disease burden, and overall quality of life. Conversely, when soils are degraded or contaminated, the negative effects cascade through food systems, public health, and ecological stability. The diagram emphasizes that maintaining soil quality is not only essential for agricultural productivity but also for sustaining planetary health, reinforcing the "one health" perspective that human, environmental, and soil systems are inseparably linked.

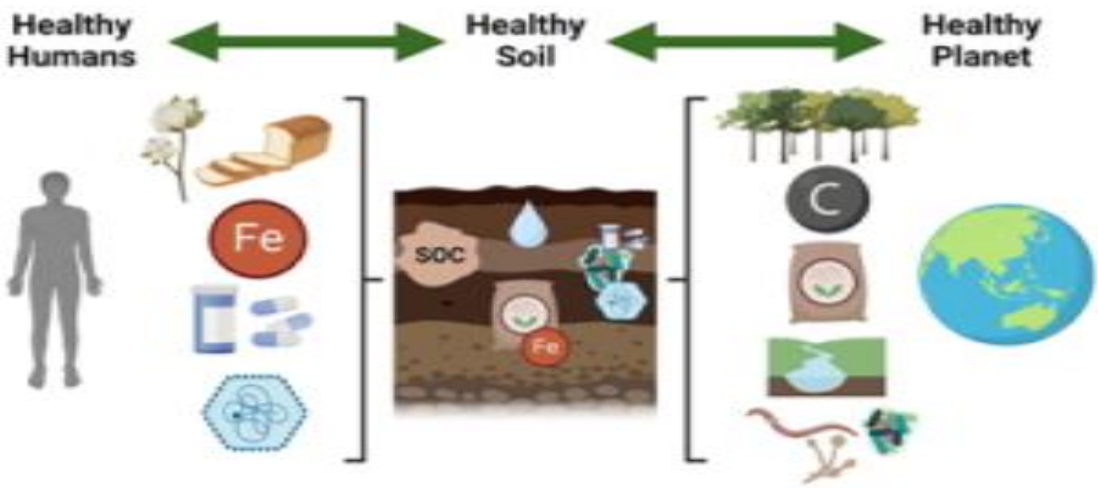

Fig. 1: Healthy humans, healthy soil and healthy planet [28]

3.2 Soil Ecosystem Services

Numerous ecosystem services that are necessary for both human well-being and environmental sustainability are provided by soil [1], [29]. It is essential to the cycling of nutrients, which involves the movement of elements like potassium, phosphorus, and nitrogen between the soil, plants, and atmosphere. These nutrients are transformed into forms that plants may absorb through the breakdown of organic matter and the actions of soil microbes, preserving soil fertility and promoting plant development [24], [30], and [31]. As water passes through the soil profile, healthy soils act as organic water filters, cleaning the water. Water can percolate through the soil's structure, trapping contaminants and keeping them from contaminating groundwater. Maintaining ecosystems that rely on clean water and safeguarding water quality depend on this filtration process [32].

One of the biggest stores of carbon on Earth is found in soils. Soils play an essential role in reducing climate change by absorbing and storing carbon dioxide from the atmosphere through a process known as carbon sequestration [33]. Decomposed plant and animal matter makes up soil organic matter, which serves as a long-term carbon sink. Enhancing soil carbon storage through techniques like cover crops and no-till farming can support international efforts to lower greenhouse gas emissions [34].

As the foundation of productive agriculture, healthy soils supply plants with essential nutrients, water, and structural support. Soils with good structure, nutrient balance, and active microbial communities yield higher crop productivity, ensuring food security [35]. However, soil degradation—caused by erosion, compaction, nutrient loss, and contamination—threatens agricultural productivity and exacerbates food insecurity, particularly in vulnerable regions [36].

3.3 Soil and Nutrition

Soil serves as the primary source of nutrients for plants, with its quality directly influencing the nutritional value of the food it produces [37]. Nutrient-rich, healthy soils support the growth of crops vital for human nutrition, while degraded soils often result in lower agricultural yields and nutrient-deficient foods [38]. This section examines the vital connections between soil quality, food security, and human health, emphasizing the role of soil in supplying essential micronutrients and ensuring their

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bioavailability for plant uptake. Table 1 highlights the interplay between soil health and human well-being.

Table 1: Effects of soil on human well-being

Aspect	Description	Impact on Human Health
Nutrient Cycling	Soil processes that recycle nutrients essential for plant growth.	Ensures nutrient-rich crops, leading to better nutrition and health.
Soil Microbiome	Diverse community of microorganisms in the soil.	Supports immune system, reduces allergies, and promotes mental health through gut health.
Water Filtration	Soil's ability to filter and purify water.	Provides clean drinking water, reducing waterborne diseases.
Carbon Sequestration	Soil's role in capturing and storing carbon dioxide.	Mitigates climate change, reducing health risks associated with extreme weather events.
Soil Contaminants	Presence of pollutants and heavy metals in the soil.	Can lead to health issues such as cancer, neurological disorders, and developmental problems.
Agricultural Productivity	Soil fertility and its impact on crop yields.	Affects food security and availability, impacting overall health and well-being.
Biodiversity	Variety of life within soil ecosystems.	Enhances ecosystem resilience, supporting sustainable agriculture and healthy diets.
Erosion Control	Soil's role in preventing erosion and maintaining land stability.	Prevents loss of arable land, ensuring long-term food production and reducing disaster risks.

4.0 SOIL QUALITY AND FOOD SECURITY

One important factor influencing food security is soil quality. The development of nutrient-dense crops is facilitated by soils enhanced with organic matter and key elements such as potassium, phosphorus, and nitrogen, which guarantee the supply of vitamins and minerals that are necessary for human health [39]. In order to combat malnutrition and avoid diet-related health problems, a link between nutrient-rich foods and healthy soils is essential [40].

4.1 Nutrient-Rich Soils and Nutrient-Dense Foods:

Crops can develop efficiently and accumulate vital nutrients required for human diets when soils offer a balanced combination of macronutrients (nitrogen, phosphorus, and potassium) and micronutrients (iron, zinc, and copper) [42]. For instance, food produced by crops cultivated in healthy soils with adequate zinc levels can help satisfy human zinc needs, which are critical for cellular metabolism and immunological function [42].

Deforestation, excessive chemical fertilizer use, erosion, and climate change all contribute to soil degradation, which reduces the soil's ability to hold onto water and nutrients [43]. Reduced agricultural yields and decreased food nutritional content are the results of degraded soils. This is particularly concerning in areas where food insecurity is prevalent, as the declining quality of soil directly contributes to poor agricultural productivity and malnutrition [7]. In regions with nutrient-poor soils, even increased food production may not translate into improved nutritional outcomes, as the crops grown in degraded soils may lack essential vitamins and minerals [44].

5.0 MICRONUTRIENT DEFICIENCIES

For plant and human nutrition, soil micronutrient availability is essential [45]. When soils lack essential micronutrients like iron, zinc, and iodine, crops grown in these soils are also deficient in these nutrients, leading to widespread deficiencies in human populations that depend on these crops as their primary food source [7], [46]. For instance, soils deficient in iron or zinc produce crops lacking these vital micronutrients, resulting in health issues such as anemia and stunted growth in humans [7], [45]. Anemia, caused by iron deficiency, affects millions worldwide, leading to fatigue, impaired cognitive development, and increased maternal mortality [47].

In children, zinc deficiency can cause development retardation, impair wound healing, and damage the immune system [48]. These deficiencies are often more pronounced in regions where soils are naturally low in micronutrients or have been degraded by unsustainable agricultural practices [49]. Addressing soil micronutrient deficiencies is essential for improving human nutrition. Crop nutritional quality

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can be improved and nutrient levels restored in the soil with the use of techniques like soil testing and micronutrient-enriched fertilizers [50]. Furthermore, methods like organic farming, crop rotation, and intercropping can increase soil fertility and encourage a more varied nutrient profile in food production systems [51].

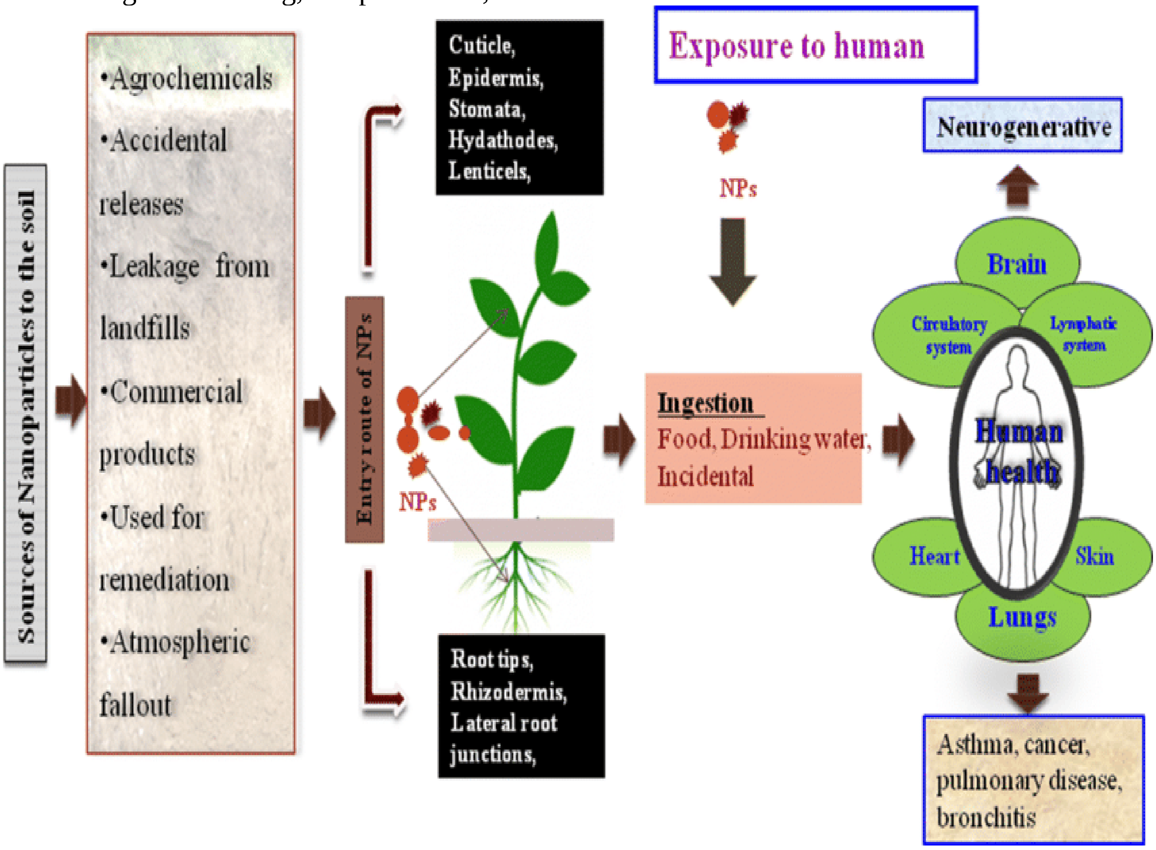

Fig 2: Overview of soil contamination and impacts on human health [52]

Figure 2 provides an overview of the pathways through which soil contamination translates into human health risks. It illustrates how pollutants such as heavy metals, pesticides, fertilizers, and pathogens enter the soil environment through agricultural practices, industrial activities, and waste mismanagement. These contaminants can then move into food, water, and air systems, creating multiple exposure routes for humans. The figure also highlights the wide spectrum of health outcomes, ranging from acute effects like gastrointestinal and respiratory illnesses to chronic conditions such as cancer, neurological disorders, and developmental impairments. By visually linking sources of soil pollution with their associated health impacts, the diagram underscores the urgent need for integrated soil management, pollution control, and public health interventions to reduce risks and safeguard well-being.

6.0 BIOAVAILABILITY OF NUTRIENTS

The extent to which the nutrients in the soil can be absorbed and used by plants is known as the bioavailability of nutrients [53]. Even when soils have adequate amounts of nutrients, the ease with which plants can absorb these nutrients can be affected by variables such soil pH, moisture content, and the presence of organic matter [54].

6.1 Soil Composition and Nutrient Uptake by Plants:

Soil composition, including factors like pH and organic matter content, significantly affects the bioavailability of nutrients [53]. For example, vital elements like phosphorus can bind to other minerals in acidic soils, making them inaccessible to plants [55]. The breakdown of organic compounds and the release of nutrients for plant uptake may also be impeded in soils with low organic matter content due to decreased microbial activity [54].

6.2 Impact on Human Diets:

The bioavailability of soil nutrients directly affects the nutrient content of the crops grown in that soil [24], [53]. If plants are unable to access critical nutrients, the resulting food will have lower levels of

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those nutrients, even if the soil contains sufficient amounts [7], [56]. Globally, it is estimated that over 2 billion people suffer from micronutrient deficiencies, much of which can be traced to soils with low bioavailable zinc, iron, and iodine [45]. For instance, soils deficient in zinc affect approximately 50% of agricultural soils worldwide, contributing to zinc deficiency in an estimated 17% of the global population [43]. Similarly, iron deficiency, linked to low soil iron availability, remains the most widespread nutritional disorder, affecting about 30% of the world's population and causing anemia in both children and women of reproductive age [47].

In soils with low phosphorus bioavailability, crops often exhibit stunted growth and reduced yields, resulting in diminished food supplies and inadequate nutrition for dependent populations [57]. Studies indicate that phosphorus deficiency affects nearly 40% of the world's arable land, posing a direct threat to crop productivity and human diets [55]. Improving the bioavailability of soil nutrients involves adopting soil management practices that enhance nutrient cycling, increase organic matter, and maintain an optimal soil pH [37]. By improving soil structure and stimulating microbial activity, methods such as composting, applying organic fertilizers, and growing cover crops can significantly increase plant nutrient uptake and improve the overall nutritional quality of the food supply [58].

7.0 SOIL CONTAMINATION AND HUMAN HEALTH RISKS

One of the biggest threats to human health worldwide is soil contamination [59]. Hazardous materials such heavy metals, pesticides, and viruses can enter the environment through industrial operations, agricultural methods, and inappropriate waste disposal, resulting in pollutants in the soil [60]. Ingestion, inhalation, or direct contact with contaminated soils can expose individuals to a variety of health problems, ranging from acute infections to chronic ailments [8], [61]. The main causes of soil pollution are examined in this part, together with the health hazards they provide and significant case studies that demonstrate the detrimental impacts of contaminated soils on human health [7].

7.1 Sources of Contamination

7.1.1 Heavy metals

Common soil contaminants include heavy metals like lead, mercury, cadmium, and arsenic, which are usually brought in by industrial processes including mining, smelting, and inappropriate waste disposal [59]. Over time, these metals may build up in the soil and become harmful to both people and plants. One of the most well-known soil contaminants, lead enters the soil primarily from industrial processes, old lead-based paints, and leaded gasoline residues [62]. Once in the soil, lead can persist for decades, posing long-term risks. Released from coal-burning power plants and industrial waste, mercury contaminates soil and water [63]. Its ability to bioaccumulate in food chains can have dangerous effects on human health, particularly affecting neurological development [64]. These metals, often byproducts of mining and industrial activities, are highly toxic even in small amounts, with cadmium linked to kidney damage and bone disorders, and arsenic associated with cancer and skin lesions [65].

7.1.2 Herbicides and fertilizers

One of the main causes of soil contamination in agriculture is the widespread use of fertilizers, pesticides, and herbicides [66]. Although the goal of these compounds is to increase crop output, misuse or overuse can have serious negative effects on the environment and human health. Globally, it is estimated that **around 4 million tonnes of pesticides are applied each year**, with over **25% misused or over-applied**, leading to soil and water contamination [67]. In developing countries alone, pesticide misuse causes approximately **385 million cases of unintentional poisoning annually**, resulting in nearly **11,000 deaths each year** [66]. Both humans and pests are poisoned by many chemicals, such as fungicides and insecticides [67]. Long-term hazards of bioaccumulation within food chains are presented by persistent organic pollutants (POPs), like DDT, which can linger in the soil for decades [61], [68]. Furthermore, excessive use of chemical fertilizers contributes to soil nitrate pollution; globally, **about 200 million tonnes of synthetic fertilizers** are applied annually, and nitrate leaching into groundwater has been linked to **over 80% of reported methemoglobinemia (blue baby syndrome) cases in rural areas** [69].

7.1.3 Pathogens in soil

Soil can also harbor harmful pathogens, including bacteria, viruses, and parasites, which often originate from livestock waste, untreated human sewage, and improper disposal of animal carcasses [70]. These pathogens pose significant health risks, especially in rural areas with limited sanitation infrastructure [71]. According to WHO estimates, **soil-transmitted**

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helminths infect over 1.5 billion people globally, causing anemia, malnutrition, and impaired cognitive development [72]. Hookworm infections alone are estimated to affect **over 400 million people**, particularly in Sub-Saharan Africa and South Asia. The bacterium *Clostridium tetani*, found in soil, causes approximately **30,000–50,000 tetanus-related deaths annually**, primarily in low- and middle-income countries where vaccination coverage is low [73].

7.2 Health Impacts

Depending on the kind and level of contaminants present as well as the length of exposure, soil contamination can result in both acute and long-term health issues [74]. From short-term consequences like skin irritation and respiratory disorders to chronic illnesses such as cancer, brain damage, and organ failure, contact with contaminated soils can result in a wide range of health problems [8], [75]. Children are particularly vulnerable, with estimates suggesting that **1 in 3 children worldwide (about 800 million) have blood lead levels above safe limits**, largely due to soil and environmental exposure [76]. Mercury exposure is also widespread, with **15 million people, many of them women and children, exposed to mercury from contaminated soils linked to artisanal gold mining worldwide** [77], [78]. Soil thus acts as a medium for various diseases that are transmitted via direct human contact [79]. For example, hookworm infections contribute to **up to 20% of iron deficiency anemia cases** in endemic regions [80], [81]. Similarly, tetanus infections from contaminated soils result in high mortality rates if untreated, with case-fatality ratios ranging between **10% and 70%**, depending on healthcare access [82].

8.0 GLOBAL IMPACTS

8.1 Flint, Michigan – Lead Poisoning Crisis

The Flint, Michigan, lead poisoning crisis is among the most well-known instances of how soil contamination affects human health [83]. Although the focus of the crisis was on lead-contaminated water, the city's soil had already been contaminated with lead from industrial pollution and lead-based paints used in homes [84]. Because children are more likely to be exposed through hand-to-mouth activities in urban settings, lead-contaminated soil is a serious problem [85]. Chronic exposure to lead in Flint led to cognitive impairments and developmental issues in many children, exacerbating the public health crisis [86].

8.2 Minamata, Japan – Mercury Poisoning

The town of Minamata, Japan, experienced widespread mercury poisoning during the mid-20th century, primarily from industrial waste dumped into the local bay [87]. Mercury entered the food chain, contaminating fish and shellfish that local residents consumed. In addition to the contamination of water, soils surrounding the industrial site also contained elevated levels of mercury, further contributing to environmental degradation [88]. The exposure led to severe neurological disorders known as Minamata disease, causing numbness, muscle weakness, and in extreme cases, paralysis or death [89].

8.3 Love Canal, New York – Hazardous Waste Site

Love Canal became infamous in the late 1970s when hazardous industrial waste buried beneath a neighborhood leaked into the surrounding soil, contaminating homes, schools, and the local environment [90]. Residents were exposed to a variety of toxic chemicals, including dioxins, leading to an increased incidence of cancer, miscarriages, and birth defects [91]. The Love Canal disaster became a catalyst for the creation of the U.S. Superfund program to clean up contaminated sites and prevent further harm to human health [92].

9.0 THE ROLE OF SOIL IN DISEASE PREVENTION

Soil, often viewed solely as a medium for agriculture, also plays a crucial role in human health beyond food production [93]. Its potential for disease prevention is being explored in various fields, from traditional medicine to modern pharmacology, gut health, and mental well-being [8], [94]. This section delves into how soil contributes to disease prevention by examining its medicinal properties, the role of soil microorganisms as probiotics, and the emerging links between soil exposure and mental health [95].

9.1 Medicinal Properties of Soil

Throughout history, soils and their components have been used for their healing properties in both traditional and modern medicine [70], [96]. Various cultures have recognized soil's medicinal potential, applying it for treating wounds, detoxifying the body, and promoting overall health [8].

9.1.1 Traditional Use of Soil-based Compounds

In many ancient cultures, clay was applied as a treatment for wounds, infections, and skin ailments [97]. Rich in minerals such as magnesium, calcium,

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and iron, clays like bentonite and kaolin have been used as topical agents for centuries due to their antibacterial, detoxifying, and absorbent properties [98]. These clays help cleanse wounds by drawing out toxins and impurities, speeding up the healing process [70], [97]. Ingested clays have also been traditionally used to treat digestive issues such as diarrhea or food poisoning, acting as a binding agent to absorb harmful substances in the gut [99].

9.1.2 Modern applications in medicine

Today, soil-based compounds continue to hold promise in medical treatments [100]. The discovery of antibiotics from soil microorganisms, such as the famous case of Streptomyces bacteria leading to the development of streptomycin, revolutionized modern medicine [101]. These antibiotics from the soil have proved essential in the treatment of bacterial illnesses and are still being studied for potential new pharmaceutical uses [8]. Furthermore, because of their anti-inflammatory and healing qualities, therapeutic clays are currently used in contemporary skincare products to treat eczema, acne, and other skin disorders [97].

9.2 Probiotics from Soil

Numerous bacteria found in soil support soil health and may possibly have positive effects on human health [8], [75]. The function of soil microorganisms, including bacteria and fungus, in enhancing gut health and fortifying the immune system has been highlighted in recent research [102].

9.2.1 Soil microorganisms and human gut health

Probiotics, commonly known for their presence in fermented foods, are beneficial bacteria that support a healthy digestive system [103]. Many of these probiotic bacteria, such as Lactobacillus and Bifidobacterium, are found in soil [104]. Traditionally, humans were exposed to soil-based organisms (SBOs) through direct contact with the natural environment and consumption of unprocessed foods [105]. These SBOs have been shown to help balance the gut microbiome, enhance digestion, and strengthen immunity [106]. Studies indicate that exposure to diverse soil microorganisms can reduce inflammation in the gut, enhance the body’s ability to fight infections, and lower the risk of chronic diseases like irritable bowel syndrome (IBS) [107], [108].

9.2.2 Immunity Enhancement

Soil-based probiotics can modulate the immune response, helping the body to better distinguish between harmful pathogens and non-threatening antigens [8]. This immune-modulatory effect is particularly important in preventing autoimmune disorders and allergies [100]. Research suggests that a lack of exposure to soil microorganisms, due to modern hygiene practices and urbanization, may contribute to the rise in autoimmune diseases and allergies, a theory known as the "hygiene hypothesis" [109].

9.3 Soil and Mental Health

A new field of research is the relationship between soil and mental health, with scientists examining the beneficial effects of exposure to natural surroundings, such as soil, on mental health [110]. This connection aligns with a broader understanding of how nature influences psychological health.

9.3.1 Exposure to Soil and Nature

Numerous studies have demonstrated the mental health benefits of spending time in natural environments, including contact with soil [111], [112]. Activities like gardening, farming, and outdoor recreation provide opportunities to interact with soil, which has been linked to reductions in stress, anxiety, and depression [113]. The existence of particular soil bacteria, including Mycobacterium vaccae, which have been shown to cause the release of serotonin, a neurotransmitter that controls mood and fosters emotions of happiness and wellbeing, may be one reason for this [114].

9.3.2 Soil Microorganisms and Serotonin Production

Emerging research suggests that certain soil microbes may act as natural antidepressants. Mycobacterium vaccae, found in soil, has been shown to stimulate serotonin production in the brain, which helps reduce symptoms of anxiety and depression [115]. Animal studies have indicated that exposure to this bacterium leads to better stress resilience and improved mood [116]. While more research is needed to confirm these effects in humans, these findings suggest that contact with soil could have mental health benefits [115].

9.3.3 Eco-therapy and mental well-being

Eco-therapy, which involves engaging with nature as part of a therapeutic practice, has gained traction as an effective approach to improving mental health [117]. Gardening, for example, not only provides physical exercise but also fosters a sense of accomplishment and purpose, which can alleviate

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symptoms of depression [118]. The act of physically interacting with soil during gardening has been shown to have a calming effect, and anecdotal evidence supports its use as a tool for reducing anxiety and promoting mindfulness [119].

10.0 STRATEGIES FOR IMPROVING SOIL HEALTH FOR HUMAN WELL-BEING

Improving soil health is essential not only for agricultural productivity but also for safeguarding human health and well-being [120]. Healthy soils are foundational to food security, environmental sustainability, and reducing exposure to harmful contaminants [7]. This section outlines key strategies for enhancing soil health through conservation practices, addressing contamination, and promoting public health interventions aimed at minimizing the risks associated with poor soil quality.

10.1 Soil Conservation Practices

10.1.1 Sustainable farming practices

Restoring and preserving soil health requires sustainable farming methods [121]. Farmers can improve biodiversity, increase soil fertility, and reduce the environmental impact of conventional agriculture by implementing practices that complement natural processes [122].

Crop rotation is the process of switching up the kinds of crops that are planted in a certain region from one season to the next. This method lessens the need for chemical pesticides, breaks up insect cycles, and helps minimize nutrient loss [123]. Additionally, it enriches organic matter and supports soil structure, which enhances water retention and lessens soil erosion [54].

10.1.1.1 Organic farming

To preserve soil fertility, organic farming emphasizes the use of natural inputs such compost, manure, and cover crops [124]. Organic farming promotes soil microbial activity and improves the soil's capacity to store carbon by eschewing synthetic fertilizers and pesticides, which benefits the climate and soil health [37], [39].

10.1.2. Role of organic matter and composting

One of the best ways to improve soil fertility and structure is to add organic matter to the soil [125]. Decomposed plant and animal matter, as well as other organic matter, enhances the aeration, nutrient availability, and water retention of soil [54], [126].

10.1.2.1 Composting

The act of turning organic waste items, such as food scraps, yard waste, and manure, into nutrient-rich compost is known as composting [127]. By restoring vital nutrients, enhancing soil structure, and encouraging the development of advantageous soil microbes, compost serves as a natural fertilizer [128]. Composting can help decrease reliance on synthetic fertilizers, minimize soil erosion, and improve soil resistance to floods and droughts by increasing the amount of organic matter in the soil [129].

10.2 Addressing Soil Contamination

10.2.1 Policy recommendations for regulating and managing soil pollutants

Preventing and managing soil contamination requires robust policies that regulate industrial waste, agricultural chemicals, and urban development practices [130]. Governments and regulatory bodies must implement and enforce policies that prioritize soil protection to ensure public health and environmental sustainability [131].

1. Regulation of agrochemicals and industrial waste

Establishing stricter regulations on the use of agrochemicals (such as pesticides and fertilizers) and industrial pollutants is critical to reducing soil contamination [132]. Governments should enforce guidelines on the safe application of chemicals and monitor industrial waste disposal to prevent toxic substances from leaching into the soil [131], [133].

2. Land use planning and urban development

Land-use policies should promote sustainable urban planning that minimizes soil degradation, such as limiting the expansion of urban areas into agricultural land and implementing green infrastructure solutions to manage stormwater runoff and reduce soil erosion [134].

10.2.2 Remediation techniques for contaminated soils

Remedial approaches can be employed to improve soil health and lessen the negative effects of pollutants when soils become contaminated. The process of phytoremediation using plants to absorb, concentrate, and eliminate pollutants from the soil is known as phytoremediation [135]. Heavy metals including lead, mercury, and cadmium can be effectively removed from contaminated soils by some plant species, referred to as hyperaccumulators

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[136]. The amount of harmful substances in the environment can be decreased by harvesting and properly disposing of these plants.

Microorganisms are used in bioremediation to degrade or neutralize soil contaminants [137]. For example, bacteria and fungi can be introduced to contaminated soils to degrade organic pollutants like petroleum hydrocarbons or pesticides [138]. This eco-friendly and cost-effective technique offers a natural solution for detoxifying polluted soils [139].

10.3 Public Health Interventions

10.3.1. Educating communities on safe interactions with soil

Public health interventions are essential for educating communities about the potential risks of soil contamination and promoting safe practices to minimize exposure, particularly in areas where soil quality is compromised [8], [140].

1. Proper hygiene after soil exposure

Individuals, especially children who may be more vulnerable to soil contamination, should be educated on the importance of proper hygiene after soil contact [141]. This includes washing hands thoroughly after gardening, playing in the dirt, or handling plants. For communities in areas with known soil contamination, additional precautions may be necessary, such as using raised beds for gardening or wearing gloves when handling soil [142].

2. Safe food production and consumption

In agricultural regions, educating farmers and communities about safe agricultural practices is essential for reducing the risk of consuming contaminated produce [143]. This includes testing soils for pollutants, using clean water for irrigation, and adopting organic farming practices to minimize pesticide residues on crops [37]. For urban gardens or areas with industrial pollution, regular soil testing can ensure that food is being grown in safe and healthy soil environments [144].

11.0 POLICY AND FUTURE DIRECTIONS

To secure a healthier relationship between soil and human well-being, a forward-thinking approach must be adopted at both policy and research levels [145]. This includes implementing regulations that protect soil from degradation and contamination, identifying key areas for further research, and integrating technological advancements that enhance soil monitoring and management [146]. This section provides a set of policy recommendations, highlights current research gaps, and explores future trends that could shape the soil-human health relationship.

11.1 Policy Recommendations

11.1.1. Governmental and international regulations for soil preservation

Policies that address pollution threats and preserve soil quality must be actively developed by governments and international organizations [130]. These regulations should encompass agricultural practices, industrial waste management, and urban development [147].

1. Soil Conservation and Agricultural Practices

By providing incentives for farmers to embrace soil-friendly techniques like crop rotation, organic farming, and conservation tillage, governments may encourage sustainable agriculture [148]. Policies could include subsidies for organic inputs and financial support for farmers transitioning to sustainable farming systems [149].

2. Control of industrial and urban soil contaminants

Strict regulations must be implemented to manage industrial waste and minimize pollution from urban development [130]. These could involve mandating the proper disposal of hazardous materials, limiting the use of harmful agrochemicals, and enforcing environmental impact assessments before large-scale urban or industrial projects [150].

3. Global cooperation on soil health

Given the global nature of environmental degradation, international bodies like the United Nations and World Health Organization should develop frameworks for transboundary soil protection [10]. These could include shared protocols for soil testing, pollution monitoring, and remediation strategies, as well as knowledge exchange on best practices for soil management and public health protection [151].

11.1.2. Mitigating contamination risks

In addition to conservation practices, policies should be enacted to address the existing and future risks of soil contamination [152]. Governments should prioritize cleaning up contaminated soils through comprehensive remediation programs [153].

1. Pollution prevention

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Policies should target the reduction of heavy metal emissions from industries, the control of pesticide use in agriculture, and the prevention of improper waste disposal [130]. Governments can mandate routine soil testing in high-risk areas and develop contingency plans for dealing with pollution incidents [154].

2. Incentives for remediation

Restoring contaminated lands can be accelerated by providing tax breaks or subsidies to businesses who invest in soil remediation methods like phytoremediation and bioremediation [155].

12.0 RESEARCH GAPS

Even while our understanding of the connection between soil and human health has advanced significantly, there are still a number of areas that need more study in order to guide successful public health and policy initiatives.

1. Soil Microbiome and Human Health

The study of how soil microbes affect human health, especially through the gut microbiome, is still in its infancy [8]. To find particular soil bacteria that may have probiotic effects and to comprehend the ways in which these microbes interact with the human body, more research is required [156]. Such studies may result in the creation of new probiotic and medicinal products made from soil.

2. Long-term Health Effects of Soil Contamination

Longitudinal studies that investigate the long-term health effects of exposure to polluted soils are needed [85]. While the short-term effects of pollutants like heavy metals and pesticides are well-known, the long-term consequences, such as chronic diseases and intergenerational health effects, have not been sufficiently studied [157].

3. Climate change and soil health

Increased soil erosion, nitrogen depletion, and changes in microbial populations are just a few of the significant impacts that climate change is predicted to have on soil health [158]. Additional research is necessary to understand how climate-induced soil degradation will affect food security and human health, and to develop adaptive strategies for mitigating these impacts [159].

4. Soil-related mental health benefits

More research is required to particularly examine soil as a factor in mental well-being, despite mounting evidence of the positive effects of exposure to natural surroundings on mental health [160]. Future studies could investigate the role of soil microbes in stress reduction, emotional resilience, and cognitive function [161].

13.0 FUTURE TRENDS

13. 1. Technological Advances in Soil Health Monitoring

Emerging technologies, such as artificial intelligence (AI) and remote sensing, offer promising tools for monitoring and improving soil health [162]. These technologies have the potential to revolutionize how we track soil conditions, manage agricultural practices, and predict risks to human health [163].

1. AI for soil management

AI-driven systems can analyze large datasets from soil sensors, drones, and satellite images to provide real-time information on soil health [162]. These systems can predict nutrient deficiencies, identify early signs of contamination, and recommend precision farming practices that optimize soil use and reduce environmental impact [164].

2. Remote sensing for soil monitoring

Satellite and drone-based remote sensing technologies enable large-scale soil monitoring, offering insights into soil moisture levels, erosion risks, and nutrient distribution [165]. These tools can be especially valuable in managing agricultural lands, detecting areas of concern before they become significant problems, and aiding in disaster response efforts in the case of floods or droughts [162].

13. 2. Implications for Public Health

As technology improves soil monitoring, public health policies can become more targeted and proactive [130]. With AI and remote sensing data, public health officials can identify communities at risk of soil contamination or degradation and implement preventive interventions before health issues arise [166].

1. Early detection of soil contamination

Technology can play a crucial role in the early detection of soil pollutants, enabling faster remediation and reducing human exposure [166]. AI algorithms can identify patterns that suggest contamination, such as irregular crop growth or unusual chemical markers in soil samples [167].

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2. Personalized agricultural practices

Future technologies could enable more personalized agricultural practices, where individual farmers receive tailored recommendations based on real-time soil data, optimizing nutrient use and minimizing exposure to harmful chemicals [168]. This could enhance both food security and the nutritional quality of crops, contributing to better human health outcomes.

13. 3. Soil and Climate Resilience

In the face of climate change, the ability to closely monitor and manage soil health will become even more critical [169]. Advanced technologies will play a key role in building climate resilience by enabling farmers and land managers to make data-driven decisions that protect soil from degradation and support sustainable food systems [170].

CONCLUSION

The connection between soil and human health is intricate and profoundly interconnected. This article emphasizes several key insights that highlight the critical role of healthy soils in promoting human well-being. Healthy soils are fundamental for growing nutrient-rich foods, regulating water and carbon cycles, and supporting essential ecosystem services. In contrast, soil contamination and degradation present serious risks to human health, leading to diseases, nutritional deficiencies, and environmental hazards. To safeguard human health, it is essential to implement sustainable soil conservation practices that preserve soil fertility, reduce contamination, and enhance ecosystem services. This includes the use of sustainable farming techniques, soil remediation efforts, and robust policy frameworks to protect soils from industrial and agricultural pollutants. Soil health is not only a matter of agricultural productivity but a crucial factor in ensuring food security, reducing exposure to harmful contaminants, and supporting mental and physical health through our interactions with the environment. The findings emphasize the need to address critical knowledge gaps in the soil-human health relationship, especially concerning the long-term impacts of soil contamination, the role of soil microbiomes in health, and the mental health benefits of soil exposure. Technological advancements, such as AI and remote sensing, present valuable tools for monitoring soil health and could play a key role in shaping future interventions. An integrated, collaborative approach is essential to tackle these challenges, involving soil scientists, public health experts, and policymakers. Soil scientists can provide valuable insights into soil composition and functionality, while public health professionals can assess and mitigate soil-related health risks. Policymakers must establish regulations that protect soil resources and promote sustainable practices. By working together, these stakeholders can ensure that soils continue to support human health, life, and ecosystems for future generations. The preservation of healthy soils is not only an agricultural or environmental issue, it's a pressing public health concern that requires immediate and ongoing attention.

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