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An inclusive evaluation of soil pollution and its remediation by chemical, physical and biological methods

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Abstract
Soil pollution occurs when the existence of some toxic elements or contaminants in the soil are in reasonably higher concentrations than the desired levels which can cause adverse effects on plants, animals and huma beings. Soil pollution can cause imbalance in the ecosystem, decrease the fertility of the soil, hinder the crop cultivation and pose health threats to the animals grazing in the fields containing contaminated soil. The excessive use of fertilizers, insecticides, pesticides, in agriculture, improper disposal waste, extensive industrialization are the root cause of soil pollution. Additionally the soil is contaminated by the presence of heavy metals like lead, mercury in the soil that are toxic for the human health. Radioactive pollutants can enter soil through mining and improper radio waste disposal that causes soil pollution. Volatile organic compounds, explosives, nuclear and electronic waste causes soil pollution. When pollutants from the soil reach water bodies they can effect water quality and make the water unfit for human consumption and irrigation. Soil pollution can be prevented by certain chemical, physical and biological methods. This review discusses the main sources and causes of soil pollution and its impact on human and plants. It further includes the remediation methods of soil pollution. Some of them addressed in this review are chemical methods such as chemical oxidation, chemical leaching or soil washing, stabilization or solidification, immobilization, electrokinetic remediation and thermal methods such as thermal desorption, smouldering, physical methods like soil vapour extraction and vitrification, biological methods such as bioremediation, phytoremediation, vermi-remediation, phytomanagement, bioventing method.

Keywords: Soil pollution, bioremediation, phytoremediation, vitrification, bioventing, phytomanagement

Introduction

The topmost layer of the earth's crust, known as soil, is a mixture of various solid, liquid, and gaseous materials that include both living and non-living elements including bacteria, organic matter that is decomposing, and mineral particles. It also contains water and air trapped in pore spaces. From weathering, or the breakdown of bed rock into particles of minerals, to soil growth and development, or pedogenesis, or the change of mineral matter through interactions between biological, topographic, and climatic elements, soil formation is a very gradual process. Depending on the local conditions, an inch of top soil may form in 200 to several thousand years. Soil, which has developed over generations to support a wide diversity of plants and serve as a habitat for a variety of microscopic and macroscopic organisms, is a significant natural resource. When pollutants, hazardous chemicals, or any other kind of contaminant are introduced into the soil in a quantity that lowers its quality and renders it habitable for organisms like insects and other bacteria, it is referred to as soil pollution. Another name for it is the addition of chemicals to the soil in amounts that are hazardous to the surrounding ecosystem and its inhabitants. The majority of this contribution is the result of human activity, including mining, contemporary agricultural methods, deforestation, careless garbage disposal, and the uncontrolled disposal of untreated industrial waste. The term "soil pollution" describes any chemical or material that is out of place, present in the soil at a concentration greater than usual, or both, and that negatively impacts any organism that is not the intended target. Soil contamination is a hidden threat since it is frequently impossible to measure or observe immediately. In addition to lowering crop yields because of hazardous contaminant levels, soil contamination makes crops grown on contaminated soils unfit for human or animal consumption. (Rodriguez *et al*. 2018) [39] From the soil, various pollutants (including important nutrients like nitrogen and phosphorus) are carried to surface waterways and ground water, where they cause eutrophication, a major environmental problem, and acute health problems for humans owing to contaminated drinking water. Additionally, pollutants directly damage bigger soil-dwelling creatures as well as soil microbes, which has an impact on soil biodiversity and the services these organisms provide. Contaminated soils are a legacy of industrialization, mining, conflict, and increased agricultural production in the World. Another term for this situation is "soil contamination," which is when a chemical or material is present in higher concentrations than would be found naturally but isn't necessarily harmful. As was previously established, anthropogenic processes are typically the source of pollution releases into the environment. Although many elements and chemicals are found in soils naturally, soil contamination is primarily caused by human activities. A change in the natural soil environment or the presence of xenobiotics (chemicals generated by humans) are the main causes of soil pollution, which is a component of land degradation. Usually, inappropriate waste disposal, chemicals used in agriculture, or industrial activity are the causes. Petroleum hydrocarbons, polynuclear aromatic hydrocarbons (including naphthalene and benzopyrene), solvents, insecticides, lead, and other heavy metals are the most often occurring compounds in these situations. earth. It poses a serious risk to people, animals, plants, and even the soil itself. The crops and farming are directly impacted by the quality of the soil, which significantly lowers agricultural yield.

Anthropogenic and natural sources

Anthropogenic sources are the primary human-caused sources of soil contamination are chemicals utilized in or generated from industrial processes, household, animal, and municipal wastes (including wastewater), agrochemicals, and goods derived from petroleum. These substances can leak into the environment unintentionally like in the case of pesticides and fertilizers, irrigation with raw wastewater, or the application of sewage sludge to land or deliberately like in the case of oil spills and landfill leaks. In addition to radionuclide deposition from atmospheric weapons testing and nuclear accidents, other causes of soil pollution include smelting, transportation, spray drift from pesticide treatments, and incomplete combustion of various compounds. (Roozbahani *et al*. 2015) [40] Natural sources includes certain pollutants which can occur naturally in soils as components of minerals and can be harmful at high concentrations, even though the bulk of pollutants have human origins.(Rodriguez *et al*. 2018) [39] When several hazardous components are released into the atmosphere during natural occurrences like volcanic eruptions or forest fires, natural pollution can also result. Polycyclic aromatic hydrocarbons (PAHs) and molecules resembling dioxin are examples of these harmful substances. Vegetable soils have been shown to contain high concentrations of heavy metals. Naturally occurring polycyclic aromatic hydrocarbons may also be found in soils. Usually originating from cosmic dust samples and meteorites, they are cosmogenic in nature. Alternatively, they may arise from the diagenetic modification processes of waxes found in soil organic matter. (Sun *et al*. 2018) [47].

Point source pollution and diffuse pollution

Due to the brine and crude oil leaks, oil and gas extraction causes significant point-source soil pollution. When pollutants are released into the soil, it might be the result of a single event or a sequence of related occurrences within a specific area. The source and identification of the pollution can be readily determined. Point-source contamination is the name given to this kind of pollution. The primary causes of point-source pollution are human activities. Former industrial sites, improper waste and wastewater disposal, unmanaged landfills, overuse of agrochemicals, various spills, and many more are examples. In metropolitan locations, point-source pollution is highly prevalent. Heavy metals, polycyclic aromatic hydrocarbons, and other pollutants are present at high concentrations in the soil near highways. Sewage sludge and wastewater disposal, old or illegal landfills, improper disposal of garbage (e.g., batteries or radioactive waste), and improper dumping of waste can all be significant point-source pollutants. (Logan *et al*. 2000) [32] Pollution classified as diffuse occurs when it is dispersed across large regions, builds up in the soil, and lacks a single, obvious source. When pollutants have been released, changed, and diluted in various media before being transferred to soil, this is known as diffuse pollution. Pollutants are transported via air, soil, and water systems in a diffused manner. Therefore, in order to properly assess this kind of contamination, complex analyses including these three compartments are required (Scholtz *et al*. 2002) [43]. Diffuse pollution can therefore be hard to track and define in terms of its spatial extent, as well as hard to analyse. Diffuse pollution can be caused by a variety of contaminants, many of which are also involved in local pollution. Some instances of diffuse pollution consist of the sources coming from nuclear power and weapons activities; unregulated waste disposal and polluted effluents issued within and around catchments; sewage sludge applied on land; agricultural use of pesticides and fertilisers that also add heavy metals, persistent organic pollutants, excess nutrients, and agrochemicals that are being shipped downstream through surface runoff; flood events; atmospheric transport and deposition in addition to soil erosion.

Main pollutants present in soil

Heavy metals and metalloids

The group of metals and metalloids with relatively high atomic masses (>4.5 g/cm^3) that can be poisonous include Pb, Cd, Cu, Hg, Sn, and Zn. This category is referred to as "heavy metals." Alongside heavy metals, (Bolan *et al*. 2014) [11] antimony (Sb), selenium (Se), and aspirin are other non-metals that are frequently taken into consideration. Low amounts of these elements are found in soils naturally. Many of them are vital micronutrients for humans, animals, and plants, but their non-biodegradable nature makes them easily accumulated in tissues and living things, which can be harmful to human health at large concentrations. Manufacturing areas, scrap from mines, high metal waste collection, leaded petrol and paints, fertiliser application, animal dung, sewage sludge, pesticides, wastewater irrigation, residues from coal combustion, petrochemical spills, and atmospheric deposition from various sources are the main human-generated sources of heavy metals. Zn, Ni, Co, and Cu (Alloway *et al*. 2013) [5]are comparatively more poisonous to plants than other heavy metals, while As, Cd, Pb, Cr, and Hg are comparatively more hazardous to higher animals. (Bradl *et al*. 2004) [12].

Nitrogen and phosphorus

All life structures, including proteins, DNA, RNA, hormones, enzymes, and vitamins, depend on nitrogen (N). It can be found in a variety of oxidation levels and in both organic and inorganic forms. The forms that are accessible vary based on the particular organism. Through microbial action, inert forms like gaseous nitrogen (N2) can be absorbed. Animals need more complicated forms, including amino acids and nucleic acids, whereas plants need more chemically accessible forms, like ammonium (NH_4^+) and nitrate (NO_3^-). When excessive amounts of nitrogen and phosphorus are added to agricultural soils as fertilisers or to regions with extensive livestock production, they turn into pollutants. These nutrients have the potential to cause eutrophication, high nitrate concentrations, and associated issues with the environment and human health when they seep into the groundwater or are carried to surface water bodies by runoff. Even while nutrients are necessary for crop productivity, applying too much of them might lower yields. Nitrogen boosts the production of chlorophyll and diverts energy meant for the extension of roots and blossom creation to the expansion of foliage, which causes diseases in plants and increases their susceptibility to pathogen attacks. Crop nutrient balance may also be impact. Pollution with nitrogen affects organic materials in the soil. In addition to affecting the makeup and activity of microbial communities, soil acidity, and salinity, nitrogen pollution also has an impact on the decomposition of organic matter in the soil. (Cachada *et al*. 2018) [16].

Pesticides

Pesticides are used to protect agricultural yields from diseases, weeds, and insect pests, so ensuring the world's food supply. Insecticides, fungicides, herbicides, rodenticides, molluscicides, nematicides, and plant growth regulators are a few examples of pesticides. Pesticides boost agricultural output, but because they have some unfavourable side effects, they can eventually bioaccumulate via the food chain and endanger living things. A portion of the pesticides sprayed on crops will stay in agricultural areas, while other portions will seep into the nearby soil, water, and air. Pesticides can travel great distances and stay in the environment for several decades. (Aktar *et al*. 2009; Cia *et al*. 2008) [4, 17].

Polycyclic aromatic hydrocarbon

An organic pollutant class known as polycyclic aromatic hydrocarbons (PAHs) is persistent and semi-volatile. A large class of physicochemically distinct compounds known as polycyclic aromatic hydrocarbons are composed of two or more unsubstituted benzene rings that have been merged together by the sharing of a pair of carbon atoms. Anthracene, fluoranthene, naphthalene, pyrene, phenantrene, and benzopyrene are the most common PAHs. High concentrations of polycyclic aromatic hydrocarbons (PAHs) in agricultural soils are caused by inadequate combustion of coal, gas, oil, and waste; pyrolysis of organic materials by industries, agriculture, and traffic; diagenetic alteration processes of natural organic matter (OM); prolonged wastewater irrigation; recycled sewage sludge; and fertiliser use in the agricultural sector. In view of its high toxicity, mutagenicity, carcinogenicity, and pervasive environmental presence, polycyclic aromatic hydrocarbons have drawn attention. Many physicochemical and biological processes, including volatilization and/or photo-oxidation to the atmosphere, irreversible sorption to soil organic matter, leaching to groundwater, abiotic loss (influence of daily seasonal temperature fluctuation), utilisation by plants, and microbial degradation, may dampen or deteriorate polycyclic aromatic hydrocarbons that enter soil. (Abdet-shaif *et al*. 2016) [1]

Emerging pollutants

Many artificial or naturally occurring compounds that have lately surfaced in the environment and are not frequently monitored are referred to be emerging pollutants. They have the potential to get into the environment and have negative impacts on human health, the environment, or both that are known or suspected. As more data or facts show that emerging pollutants are endangering human health and the ecosystem, they may likely become pollutants of increasing concern. Chemicals like hormones, endocrine disruptors, medicines, and poisons are examples of emerging pollutants. Biological pollutants include bacteria and viruses that are found in soil along with other micropollutants. (Beam *et al*. 2006) [9].

Radioactive substances and nanoparticles

Nuclear accidents, mining, and inappropriate disposal of radioactive waste are some of the ways that radioactive contaminants, including uranium, radium, and caesium, can find their way into the soil. On the other hand, nanoparticles can enter the soil through a variety of activities, including wastewater treatment and industrial processes. They can also originate from created nanoparticles and nanoparticles found in pollution particles, such as carbon nanotubes. Ecosystem impairment caused by soil pollution is given in figure 1. These compounds have the potential to cause radiation exposure, which can have long-term effects on soil quality and pose serious concerns to both human health and the ecosystem. (Beam *et al*. 2006) [9].

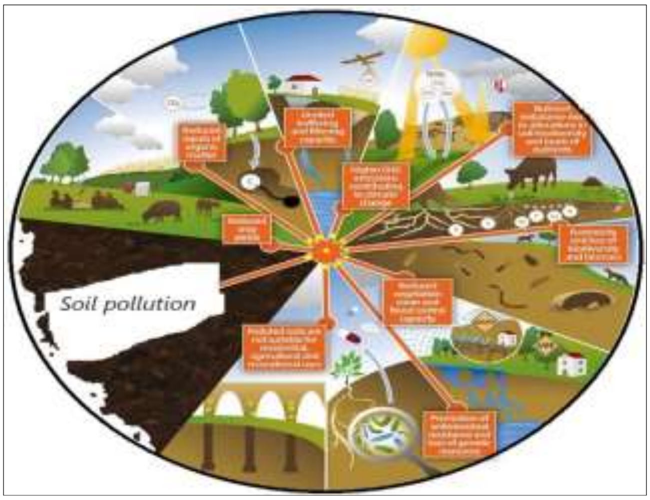

Fig 1: Ecosystem impairment caused by soil pollution

Causes of soil pollution

1. **Radioactive Pollutants:** Radioactive materials from nuclear testing facility explosions, radioactive fallout, and companies producing radioactive dust and wastes seep into the ground and build up, causing soil contamination. For instance. Nuclear reactors generate waste that includes the major nuclides Sr-90, which has a half-life of 28 years, and Cs-137, which has a half-life of 30 years, as well as elements such as lanthanum-140, iodine-131, barium-140, cesium-144, and ruthenium-106. Sr-90 and Cs-137 are carried by rainwater and deposited in the soil, where they are strongly bound to the soil particles by electrostatic forces. Gamma radiation is emitted by every radionuclide that has been left in the soil.
2. **Modern Agricultural Practices:** Pesticides and agrochemicals like fertilisers and animal dung are among

the various agricultural sources of soil pollution. Because these agrochemicals can alter plant metabolism and reduce crop output, trace metals including Cu, Cd, Pb, and Hg are also regarded as soil contaminants. Over the past few decades, synthetic chemical pesticides and fertilisers have been widely utilised to improve the yield from limited land area in order to fulfil the growing need for food for an ever-increasing population. However, this has resulted in soil toxicity. When they combine with water, they seep into the ground and gradually lower the soil's fertility. Additional chemicals alter the soil's composition and facilitate air and water erosion. Many of these pesticides are absorbed by plants, and when they break down and become a part of the land, they contaminate the soil. (Knoepp *et al*. 2005) [29].

3. **Industrial and Mining Activities:** The main cause of soil contamination is the proliferation of industries that have emerged since the beginning of the industrial period and lack adequate waste management systems. Since ancient times, mining has had a significant effect on the land, water, and biota. Since the majority of industries rely on the extraction of minerals from the Earth, there has also been an expansion in mining and manufacturing. Numerous contaminants have entered the soil as a result of metal smelting for separating minerals. Significant amounts of heavy metals and other hazardous substances are released into the environment by mining and smelting plants; The by-products, whether they are coal or iron ore, are contaminated and not disposed of in a way that is safe. Consequently, industrial waste left on the soil's surface for an extended length of time erodes it. (Beam *et al*. 2006) [9].
4. **Lack of proper Waste Disposal:** Both urban and rural modern lifestyles generate enormous amounts of garbage, and the issue of soil pollution is exacerbated by a lack of waste management practices. Urban wastes include the following: garbage and rubbish materials such as plastics, glasses, metallic cans, fibres, paper, rubber, street sweepings, fuel residues, leaves, containers, abandoned vehicles, and other discarded manufactured products; they also include commercial operations and domestic wastes such as dried sludge and sewage. The main sources of worry are plastic and other non-biodegradable garbage. (Beam *et al*. 2006) [9].

- **Industrial wastes:** Soil pollution is mostly caused by the improper disposal of industrial wastes. Sources: Industrial pollutants are primarily released by a variety of sources, including chemical fertilisers, pulp and paper mills, oil refineries, sugar factories, tanneries, textiles, steel, distilleries, coal and mineral mining industries, pharmaceuticals, glass, cement, petroleum, and engineering industries, among others. Impact: The chemical and biological characteristics of soil are impacted and changed by these contaminants. Because of this, dangerous substances may find their way into the food chain of humans through the soil or water, disrupt biochemical processes, and ultimately have a major negative impact on living things. (Gaikwad *et al*. 2023) [21].
- **Urban wastes:** Sewage and dried sludge are among the household and business wastes that make up urban wastes. Most people refer to all urban solid garbage as "refuse." Urban refuse's components include: Garbage and trash items such as plastics, glasses, metal cans, fibres, paper, rubber, street sweepers, fuel remnants, leaves, containers as well, abandoned cars, and other produced goods are included in this refuse. Even though they should be disposed of separately from industrial garbage, urban household wastes might nonetheless be hazardous. This occurs as a result of their resistance to degradation. (Gaikwad *et al*. 2023) [21].

5. **Discharge of sewage:** Severe soil pollution can arise from the overuse and ineffective application of chemical pesticides. Wastewater can contribute to soil pollution by allowing toxins to seep into the soil when it is released into the environment without being properly treated. The health of ecosystems, human welfare, and soil quality may all suffer as a result. Organic matter, pathogens, heavy metals, nutrients (such phosphate and nitrogen), and different chemical compounds are some of these contaminants. These compounds may negatively impact plant development, soil fertility, and the general equilibrium of the soil ecosystem. The presence of organic materials in untreated wastewater can stimulate soil microbial activity, which can cause nutrient deficiencies and oxygen depletion. (Gaikwad *et al*. 2023) [21].
6. **Electronic waste;** Referred widely as "e-waste," it is made up of a number of substances that, because of their toxicity, may be hazardous to human health. When e-waste is improperly disposed of, these dangerous materials may leak into the ground and affect nearby ecosystems and living organisms. Electronic equipment like computers, cell-phones, televisions, and other electrical appliances are referred to as e-waste.(Barba-Gutirrez *et al*.2018) [8] Hazardous compounds such as lead, mercury, cadmium, bromine-based flame retardants, and other poisonous substances are frequently found in these gadgets. The inappropriate management or disposal of e-waste in open dumping sites or landfills can cause leaching and runoff, which can release these harmful components into the soil over time. These pollutants can harm the ecosystem and living things if they get into the soil. The tainted soil can harm plant development, reduce soil fertility, and upset the ecosystem's delicate equilibrium. (Gaikwad *et al*. 2023) [21].
7. **Coal ash:** The fine particles created when coal is burned in boilers are referred to as coal ash, sometimes called fly ash. These microscopic particles are released into the flue gases that are produced during the burning of coal. The size of these fly ash particles might range from a few micrometres to submicron levels. It's crucial to remember that fly ash includes traces of harmful substances like mercury, cadmium, and arsenic. These substances can concentrate in fly ash during burning and are found naturally in coal. Because of their toxicity, arsenic, cadmium, and mercury are recognised to be harmful to both human health and the environment. Fly ash spills from coal-fired boilers can have a big impact on soil and water contamination, not to mention air quality. Particles of fly ash have the potential to pollute soil and release harmful substances into the surrounding environment as they fall to the ground. This may put human populations close to power plants burning coal at risk as well as ecosystems that support plants, animals, and microorganisms. (Dhakal *et al*. 2007) [18].
8. **Corrosion of underground storage tanks:** Storage tanks are essential for securely holding a variety of chemicals and materials. But these tanks can break down with time, which might result in corrosion and possible

leaks. The stored chemicals could leak out of the corroding tanks and into the surrounding soil, contaminating it and changing its chemical composition. Soil pollution could occur if storage tanks containing hazardous chemicals or materials that can change the chemistry of the soil start to erode. (Aichner *et al*. 2013) [3].

9. **Nuclear wastes:** There are serious risks to human health associated with the improper disposal of nuclear waste. It is possible for radioactive waste to make a place uninhabitable if it is not handled and disposed of in a safe and acceptable manner. A byproduct of different nuclear operations, such as power generation, research, and medical uses, is nuclear waste. It contains extremely radioactive compounds that can linger in the environment for a very long time and release dangerous radiation. Nuclear waste can have detrimental effects on both human health and the local ecology if it is not properly controlled and stored. Unsafe disposal of nuclear waste increases the danger of radiation exposure and contamination. The waste's radioactive components can seep into the ground, water, and air, dispersing radiation and seriously endangering the health of any living thing. (Gaikwad *et al*. 2023) [21].
10. **Accidental Oil Spills:** Chemical storage and transportation might result in oil spills. The majority of petrol stations display this. Because of the fuel's chemical composition, the soil becomes unusable for cultivation. Through soil penetration, these substances can contaminate groundwater and render it unfit for human consumption. There is a chance that when mineral oil is being extracted from the oil fields, there may be an oil spill and that the crude oil will contaminate the surrounding soil. The compounds in the mineral oil raise the pH of the soil and lower its phosphorus content. As a result, the soil's basic makeup changes and the temperature rises overall. (Sachan *et al*. 2023) [41].
11. **Biological Agents:** Excreta from people, animals, and birds finds its way into the soil, which is one of the main ways that biological agents pollute land. For instance, if manures and digested sludge are applied heavily, plants may suffer significant harm in a matter of years.
12. **Acid Rain:** Acid rain is another factor that pollutes soil. When airborne contaminants combine with precipitation and return to the earth, acid rain is produced. Some of the vital nutrients in the soil may be dissolved by the contaminated water, altering the soil's composition. As a result, plants and important soil microbes may suffer from this corrosive rain, which might eventually upset the food chain. (Srawn *et al*.2019) [46] Rainwater's acidic composition changes the pH of the soil, causing acidification. A change in pH can have an impact on a number of soil features, such as the availability of nutrients, microbial activity, and the dissolution of minerals and metals. The development and growth of plants may be hampered in acidic soils by the loss of vital minerals including calcium, magnesium, and potassium. (Abrahams *et al*. 2002) [2].
13. **Pathogens:** Microbes that cause disease are known as pathogens. Not all microorganisms are good; some can cause disease. This is true even though soil biodiversity is incredibly complicated, with billions of bacteria, fungi, protists, and other creatures. Sludge from sewage systems, manures, and the burial of human and animal remains are just a few of the places where pathogenic bacteria can be found in soil. Animal excrement can serve as the source of some infections. Therefore, through skin contact or interaction with polluted water and food, soil becomes the principal source of contamination. (Sparks *et al*. 2019) [44].
14. **Transportation:** One of the primary causes of soil contamination in and around metropolitan areas is activities related to transportation. Lead contamination of soils from lead petrol is a significant persistent source of soil pollution related to transportation. (Mathews *et al*. 2016) [33].
15. **Acidification and crop loss:** Since acidification of agricultural soils can release heavy metals that are harmful to plants, it can also lead to more soil contamination. The primary source of soil acidification and salinization via nitrogen fixation and other N-transformation processes has been determined to be an excess of nitrogen in the soil. The natural processes lead soils to acidify over hundreds to millions of years. However, agricultural practices, particularly excessive N fertilisation, greatly speed up this process, lowering soil pH by 0.26 pH. When the amount of nitrogen added to agricultural soils exceeds what is needed by plants, nitrification microbial activity will cause an accumulation of nitrates (NO_3^-), which are very soluble and can easily contaminate groundwater. Microbial biomass and activity rise in response to increased soil nutrient availability, but microbial biodiversity is changed, leading to nutrient cycle imbalances. (Bhum *et al*. 2005) [10].
16. **Manure:** Applying untreated manure may result in heavy metal pollution, which affects nutrient availability and cycling while also changing the size, makeup, and activity of the community of microbes. These modifications also have a negative impact on a number of plant quality and yield-related parameters.
17. **Soil Erosion:** Erosion of the soil occurs frequently. Erosion is the process of topsoil loss. It happens whenever any physical activity dislodges and carries away the weathered soil particles. This physical agent could be any of the anthropogenic activities like mining, building, clear-cutting timber, development of agriculture, and overgrazing, or it could be some natural processes like wind, rain, volcanic activity, etc. Because of all these human activities, the land is left vulnerable to the effects of high winds and swiftly moving water. Powerful winds speed up the drying process and remove the valuable soil, depositing it somewhere as dust or sandstorm. Similar to this, heavy downpours that frequently occur in these places lead to significant soil erosion. Desiccation, or the drying out of the soil, and desertification follow soil erosion. The top layer of the soil, which is essential to the fertility of the soil, is lost as a result of soil erosion. Even though it can be shed quickly, it takes between 500 and 1000 years for one inch of the top layer to accumulate. In our nation, the greatest loss of farmland soil has been recorded. It accounts for approximately 18.5% of the global farmland soil loss. (Logan *et al*. 2000) [32].
18. **Salinity, Acidity and Alkalinity of the Soil:** They lower the fertility of the soil. A tube well or a river are common sources of water for crop irrigation. Salts abound in these fluids, which are retained when water dissipates or is transpired by crops. Thus, over time, the soil becomes contaminated with salt. Once more, minerals like calcium carbonates and alkaline compounds which would

normally stay dispersed throughout soil due to a high water content are not leached and instead tend to be deposited in areas with little rainfall and dry temperatures. Due to this process, the soil becomes naturally alkaline, which is detrimental to the growth of some crops. When the concentration of hydrogen ions in the boil rises, the soil turns acidic. greater of these ions result in greater. Some of the causes of soil pollution is given in figure 2.

19. **Deforestation:** Deforestation, or the large-scale removal of trees, is a primary cause of land contamination. Over time, powerful winds and flowing water force the tree roots that bond the soil to break off. In regions with hills and mountains, trees are even more significant because they stabilise large rocks. Landslip frequency has increased due to activities like blasting, tree-cutting, and construction in mountainous terrain. (Sreemeenakshi *et al*. 2021) [45].

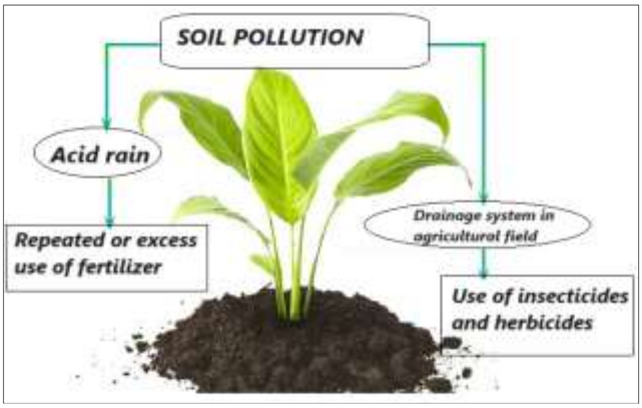

Fig 2: Causes of soil pollution

Impact of Soil Pollution on human and vegetation

Impacts of soil pollution are not confined to soil and its biota but are carried over to every aspect of the environment and affect every organism from the earthworm to humans. Some of the adverse effects are as follows.

Effects on human health

This is the manner in which pollution from the soil gets to us because we are food-dependent on the land. Our bodies bioaccumulate poisons, which can result in chronic poisoning and a host of other illnesses. These days, there is a rise in issues related to reproductive health, birth and developmental problems, neurologic consequences, nutritional deficiency and variations in body cells that cause cancer. The negative consequences that exposure to contaminated soil can have on human health are referred to as soil pollution's health implications. These ramifications cover a broad spectrum of health issues, including both short-term and long-term consequences. (Brevik *et al*. 2013; Bilnemann *et al*. 2006) [13, 14]

Respiratory disorders: Particularly under dry and windy conditions, soil contamination can release chemicals and particulates into the atmosphere. Breathing in these particles can lead to respiratory issues, including bronchitis, asthma, and other pulmonary conditions. Harmful compounds included in dust and particle debris can irritate the respiratory system and impair lung function. (Haider *et al*. 2024) [24].

Skin conditions: Dermatological conditions and irritations may arise from direct contact with polluted soil. Rashes, allergic responses, and skin infections can be brought on by toxic elements found in soil, such as heavy metals and certain chemicals. If preventative precautions are not taken, prolonged exposure to polluted soil might worsen these skin problems.

Toxicological effects: Heavy metals, insecticides, and industrial chemicals are just a few of the pollutants that can enter the human body via direct contact with the soil or ingestion of contaminated food or water. Over time, these contaminants may build up in the body and have toxicological effects. They can harm tissues and organs, obstruct essential physiological functions, and accelerate the onset of a number of disorders. (Bilnemann *et al*. 2006) [14].

Waterborne illnesses and infection: Soil pollution has the potential to pollute surrounding water sources, such as surface and groundwater. Pollutants have the potential to transmit waterborne illnesses when they seep into bodies of water. Drinking water supplies can get contaminated by pathogens, chemicals, and other toxins found in the soil. This can result in microbial infections, gastrointestinal diseases, and other health problems related to drinking water.

Carcinogenic effects

Certain heavy metals, chemical compounds, and persistent organic pollutants are among the pollutants found in soil that are either confirmed or probable carcinogens. Long-term exposure to these carcinogens through polluted soil can raise the risk of getting skin, liver, kidney, and lung cancer, among other cancers.

Effects on vegetation

It is impossible for plants to adjust to abrupt changes in the soil. Soil erosion is caused by fungi and bacteria that are present in the soil but are unable to bind the soil owing to chemical changes. Huge swaths of land turn into desolate areas that cannot sustain life. The poisons will be absorbed by the plants that do develop on these areas and move up the food chain. Cu and Al heavy metals, respectively, produce chlorosis in leaves and changes in the ultrastructure of roots. Anthracene, naphthalene, and pyrene are examples of polyromantic hydrocarbons (PAHs) that impair photosynthetic efficiency, pigment loss, and protein composition changes. Because they are persistent, persistent organic pollutants (POPs) such as insecticides are harmful to plants, causing burns, stunting, necrosis, and chlorosis. Radionuclides such as $^{137}C_s$ mimic potassium and replace it, obstructing the flow of water and nutrients into plants. The build-up of Cs in leaves also affects the physiological function of plants. Antibiotics such as tetracycline impede plant growth, whereas microplastics are hazardous to plant roots. Plants are impacted by acid rain-polluted soils because they alter the chemistry of the soil and make it harder for plants to absorb nutrients and carry out photosynthesis. Effects of soil pollutants on vegetation is given in Table 1. (Rodriguez *et al*. 2018) [39] The capacity of the soil to buffer pH variations can be compromised by acidic deposition, which can lead to unfavorable conditions that kill off plants. (Lithner *et al*. 2011) [31].

Table 1: Effects of soil pollutants on vegetation.

Soil pollutants	Effect on vegetation
PAH's	Inhibits photosynthetic performances.
POP's	Plants may experience chlorosis, necrosis, stunting, burns, twisting of the leaves, inadequate root hair production, and yellowing of the shoots.
Heavy metals	Decreases photosynthetic and transpiration rate.
Radionuclides	Affects the movement of water and nutrients.
Micro pollutants	Toxic for root and inhibits plant growth.

Some other effects of soil pollution

Reduced Soil Fertility: The presence of hazardous substances in the soil can lead to a reduction in soil fertility and, consequently, in soil yield. After that, the polluted soil is used to grow fruits and vegetables that are deficient in nutrients and might contain harmful substances that could pose a major risk to the health of those who eat them. Impact on the environment and odour pollution is mainly due to the huge amounts of trash and waste that are thrown out in the open and scatter over a region detract from the peace and quiet of the surroundings. The discharge of noxious and malodorous fumes from waste sites contaminates the surrounding ecosystem and has detrimental impacts on certain individuals' health. Other people are inconvenienced by the offensive odour. (Cachada *et al*. 2018) [16] It also contamination of water source. Raindrops carry polluted soil into water sources by surface runoff, which results in water pollution. Additionally, pollutants may seep down and contaminate groundwater. For this reason, the tainted water is unsafe for human and animal consumption. Since the creatures that inhabit these bodies of water will find their environments uninhabitable, it will also have an impact on aquatic life.

Soil remediation technologies

After the contaminated soil has been excavated, physical, chemical, and biological approaches are used in remediation technology, which can be applied in situ or ex situ. Typically, the cleanup process involves removing pollutants from the area and changing them into less harmful forms. (Sapkota *et al*. 2022) [42].

Chemical Methods of Soil Pollution Prevention

Chemical approaches try to stabilize pollutants and change them into less hazardous forms that are safe for plants, animals, and people by adding chemicals or solvents to the polluted soil. For soil remediation, a variety of chemical therapies are accessible, such as electrokinetic remediation, and chemical leaching and fixing. These techniques are quick, easy, and affordable to use on the spot. (Burgess *et al*. 2013) [15].

Chemical Oxidation

Chemical decontamination methods, which include infusing reactive chemical oxidants into the soil and groundwater to swiftly and totally eliminate pollutants, are centered around chemical oxidation. Chemical oxidation in situ (ISCO) is a versatile technique that is particularly useful for eliminating contaminants from difficult-to-reach areas such as deep soils or soils beneath structures. Chemical oxidation is a versatile treatment approach that can be used to treat a wide range of organic pollutants, such as TPH, BTEX, and PCBs. To eliminate chemical pollutants that are already present in the contaminated medium (soil or groundwater), ISCO is carried out by adding potent chemical oxidizers to it. Numerous organic molecules, including those that are impervious to natural deterioration, can be remedied using it. ISCO has demonstrated efficacy in remediating specific organic pollutants, including trichloroethene and tetrachloroethene, which are chlorinated solvents, and compounds related to gasoline, such as benzene, toluene, ethylbenzene, and xylenes. Chemical oxidation can reduce the toxicity of some other pollutants. It is possible to employ oxidizing agents such as potassium, sodium, and persulphate permanganate. (Abrahams *et al*. 2002) [2].

Stabilization or Solidification

"Solidification and stabilization" is a remediation strategy that aims to prevent or postpone the release of hazardous chemicals from wastes, such as contaminated soil, sludge, and silt. These methods usually do not destroy the contaminants. By encasing the waste in a solid block of material, solidification seals the waste in place. This block is less water-permeable than the rubbish. Stabilization results in chemical reactions that lessen the possibility of contaminants seeping into the environment. They are often used in tandem to prevent human and wildlife exposure to contaminants, particularly metals and radioactive ones. One way to improve the properties of soil is through soil stabilization, which involves adding and combining different materials. Soil stabilization is the process of improving the resistance to shear properties of the soil, which in turn increases the soil's carrying capacity. As a corrective measure, soil stabilization procedures strengthen the soil's shear strength, decrease its permeability and compressibility in earthen structures, and help to keep buildings from settling. Lime or cement can be added to stabilize soils. These stabilization procedures yield better building materials and enhance the stabilized soil's numerous engineering qualities. The benefits of soil stabilization include an increase in soil strength, durability, stiffness, and a decrease in soil flexibility and propensity for swelling and shrinking. (Firoozi *et al*. 2017) [20].

Immobilization

Hazardous metal immobilization stops inorganic metals from being taken by plants by transforming them into organic form using a range of materials, microorganisms, chemicals, or plants. For horticultural crops, a variety of immobilization materials, such as diammonium phosphate, biochar, limestone, phosphorite, wood ash, red mud, chelates like ethylene diamine tetraacetic acid (EDTA), silica treatment, gypsum, and other compounds with metallic immobilization properties, have been used and are accessible to reduce metal toxicity. Through a variety of processes, including adsorption, the formation of minerals containing heavy metal complexes, redox reactions, and precipitation, immobilization material alters the pH of the soil, improves both the physical and chemical attributes of the pollutants, and increases the availability of N, P, and K. Additionally, it lowers the amount of heavy metals. A few of the known uses for chemical immobilization materials are discussed, including the following: applying red mud raises the pH of the soil and dramatically lowers the phytoavailability of Cd and Pb; using alkaline organic treatments lowers plant uptake of these dangerous heavy metals, thereby lowering human exposure to toxic levels of Cd, Pb, and Zn. It has previously been demonstrated that adding peat and rock phosphate to soil contaminated with heavy metals lowers the availability of Pb, Cd, and Cu to plants. The solid substance known as biochar, which is produced when plant-based leftovers break down, is thought to have significant potential for improving long-term carbon sequestration, raising pH levels, increasing cation exchange capacity, and increased soil production by the adsorption of metal contaminants (Cd, Cr, Hg, Ni, and Cu) in soils. The low-cost soil amendment of calcined cockle shell has also been proposed, together with lime that effectively immobilizes Cd, Pb, and Zn. Metals are rendered immobile by silica treatments, which cause the formation of metal hydroxides and silicates. Chemicals such as hydroxyapatite were useful in reducing the mobility of lead, zinc, copper, zinc oxide, and arsenic. (Mishra *et al*. 2021) [34].

Soil washing

One method of ex-situ remediation is soil washing. Physical separation is used to separate the pollutants from the soil, and then chemical leaching using a chemical solvent is employed. It is based on the idea that the majority of pollutants, both organic and inorganic, have a tendency to attach to smaller soil particles. As a result, washing procedures separate the larger, coarser-grained particles like sand and gravel from the smaller, clay and silt particles. Essentially, it concentrates the pollutants into a smaller volume of soil (sludge), which can then be disposed of in an authorized landfill or treated further using a variety of alternative remediation technologies such chemical oxidation, thermal desorption, and bioremediation. Ultimately, the coarse-grained portion is returned to the site of excavation. This technique frequently serves as a pre-treatment phase in other remediation procedures since it greatly lowers the initial volume of contaminants contained in soil. Different organic and inorganic contaminants, such as volatile organic compounds (VOCs), pentachlorophenol (PCPs), polychlorinated biphenyl (PCBs), pesticides, heavy metals, radioactive elements, petroleum and fuel residues, etc., can be efficiently removed from soil by using soil washing procedures. The grain size distribution of the soils that need to be treated is one of the main factors that determines whether soil washing is appropriate at a given location. Soil cleaning will be more effective the lower the amounts of silt, clay, and organic matter (greater hydraulic conductivities work better). If the pollutants cling firmly to the soil particles, soil washing might not be appropriate. Therefore, the pollutants on the soil surface are not usually completely removed by the washing procedure. To completely clear the soil in this case, another remediation method would be needed. In order to set up the contaminated soil for treatment, it must first be excavated and then moved to a staging location. Following the first treatments, the soil is screened in order to essentially get rid of big trash, pebbles, and other things. Following screening, the residual materials are fed into the soil scrubbing machine, where they are combined with a washing solution to extract any leftover impurities. The soil particles settle in the wash water according to their grain size. Both of the soil particles and the wash water are examined for pollutants once they have settled. They are returned to the site or put to further use if they are deemed to be clean. However, they go through additional treatments if there are any contaminants. (Khasanova *et al*. 2023) [28].

Thermal Methods of Soil Pollution Prevention

Heat is utilized to raise the temperature below the surface, which purges the groundwater and soil of pollutants.

1. Thermal Desorption

Thermal desorption is a remediation method for clearing contaminated soils. This method, which works only with volatile pollutants, uses heat to evaporate the pollutants. Hydrocarbon-based organic wastes make up the majority of them. Administering heat to contaminated soils causes wastes with low boiling points to evaporate; this vapour can then be collected and processed in an off-gas treatment facility. This removes any worries about contaminating in the event that the soil is used for other purposes in the future. Since landfill space can usually be saved and soil can usually be restored without needing to be carried elsewhere, this benefit is commonly viewed as advantageous. (Rare *et al*. 2011) [37].

2. Smouldering

Smouldering in the clean-up, the largest and longest-lasting flames on Earth have naturally happened in peat and coal deposits. Smouldering is a flameless combustion process that propagates an exothermic combustion wave that is self-sustaining provided that the fuel and oxygen requirements are met. During combustion, the contaminants are converted to heat, carbon dioxide, and water, thus no further fuel is needed to complete the cleanup. Despite regional and temporal temperature fluctuations brought on by smoldering, the average.

Electrokinetic Remediation

To implement the electrokinetic remediation approach, an electric current is applied to both sides of the contaminated soil to create an electric field gradient. Contaminants are transported to the poles by electromigration, electroosmotic flow, and electrophoresis in the presence of an electric field. This approach protects the natural ecosystem because it is simple to use and poses no environmental risks when applied on permeable soil. The pH of the soil cannot be maintained via direct electrokinetic remediation. To regulate the pH level, certain buffer solutions must be added to the cathode and anode. For the treatment of both saturated and unsaturated soils, this method works quite well. In addition to the contaminants, the presence of hematites, carbonates, and gravel reduces the cleanup efficacy of this approach. Combining electrokinetic remediation with other methods including "permeable reactive barrier" (PRB), electrokinetic-microbe combined remediation, and electrokinetic-oxidation/reduction combined remediation can increase its efficacy. However, there are still a number of obstacles to overcome before using electrokinetic technologies for soil remediation, including the use of electric energy and the negative effects of electricity on soil properties. (Koul and Taak *et al*. 2018) [30].

Biological methods of soil pollution prevention

More creative and long-lasting biological soil restoration methods are being developed these days. By using a biological approach, soil contaminants are successfully removed, soil ecotoxicity is reduced, and soil health and associated ecosystem services are restored.

Phytoremediation

Although these techniques are applicable to soil contaminated with either organic or inorganic materials, they are most commonly applied to metal-contaminated soil. (Glick *et al*. 2003) [23] The two most popular methods of phytoremediation are phytoextraction and phytostabilization. One scientific, economical, and environmentally sound method that works well in underdeveloped nations and is seen as a lucrative commercial venture is phytoremediation. Regretfully, in several nations, including our own, the technique has not yet been commercially employed as a technology, despite its potential. Phytoremediation is the process of eliminating contaminants from water and soil or lowering the hazards of environmental pollutants such as heavy metals, rare elements, organic compounds, and radioactive materials. It is accomplished by using green plant engineering, such as herbaceous and woody species. (Khakbaz *et al*. 2012) [27]

Depending on the particular plant mechanisms involved and the kinds of toxins being addressed, phytoremediation involves a variety of approaches, each of which is briefly described here.

1. **Phytostabilization:** This method stabilizes and immobilizes contaminated soils by using plant species that can withstand pollution. It essentially stops pollutants from being eroded away by wind and water. By lowering soil moisture and leachate flow, the evapotranspiration mechanism of plants assists in preventing toxins from migrating farther into the soil and safeguards groundwater against contamination.
2. **Phytoextraction:** This remediation technique entails the direct uptake of organic and inorganic pollutants into plants from the soil. The particular pollutant and the plant species involved determine the amount and pace of contaminant transport from the roots to the aboveground portions of the plant. While organic pollutants can undergo biodegradation and provide soil microorganisms with energy and carbon, trace elements are unable to chemically cleansed and are not biodegradable. Rather, they may infiltrate living things' tissues, whereupon they may accumulate (a process known as bioaccumulation) and concentrate (a process known as biomagnification) throughout the food chain. (Sachan *et al*. 2023) [41]
3. **Phytovolatilization:** In order to convert and volatilize both inorganic and organic pollutants within the plant-microorganism-soil system, specialist plant enzymes are used in the remediation process. Through this process, the pollutants are moved from the soil into the plants, where they change before being released into the atmosphere. This method has been effectively used to remediate soils that contain both organic and inorganic mercury contamination. Under such circumstances, the plants are able to convert the more hazardous Hg^{2+} into elemental mercury, which is subsequently released into the atmosphere.
4. **Phytodegradation:** It is a process by which organic pollutants in the soil break down with the help of plants. Plants have the ability to accelerate the breakdown of organic contaminants through a variety of methods, either by mineralizing them into simpler compounds or changing their hazardous forms. The primary cause of this natural breakdown process is the action of enzymes made by related microbes and plants. Because it uses plants' innate ability to detoxify and break down organic contaminants in the soil, together with the microbial communities that accompany them, phytodegradation can be a successful remediation method for contaminated locations.
5. **Rhizodegradation:** It describes the breakdown of organic pollutants in soils that is aided by the activities of microbes and fungi found in the soil root. The interaction between the plants and these microbes is what drives this process, and the exudates that the plants generate from their roots are essential. Through co-metabolism, these exudates can increase the variety and activity of microorganisms, facilitating the biotransformation of organic pollutants. (Cachada *et al*. 2018) [16].

Bioremediation

Bioremediation, or using microorganisms (mainly bacteria and fungi) to clean up contaminated areas, is a sustainable method of cleaning up contaminated soils. While bioremediation can also be used to treat organic pollutants such as mineral oils, pesticides, polycyclic aromatic hydrocarbons (PAHs), petroleum hydrocarbons, polychlorinated biphenyls (PCBs), etc., it is more frequently used to treat inorganic pollutants. Utilizing soil microorganism activity, bioremediation is an in situ biological treatment technique used to clean up contaminated locations. Its main focus is on the alteration of trace element species to decrease their availability and the breakdown of organic contaminants including insecticides, solvents, and petroleum hydrocarbons. Both aerobic and anaerobic bioremediation are possible, and several treatment techniques can be used depending on the pollutants and operational circumstances. Airborne oxygen is used in aerobic biological therapy, and it is occasionally added to the soil to encourage the growth of aerobic microorganisms. Anaerobic biological treatment, on the other hand, eliminates oxygen and frequently adds reducing chemicals to promote microbial activity. Even though both methods can degrade some contaminants, anaerobic biological treatment is better suited for highly chlorinated hydrocarbons, while aerobic biological remediation is usually used for non-chlorinated or mildly chlorinated hydrocarbons. (Hickman *et al*. 2008) [25].

Vermiremediation

Vermiremediation is the process of employing earthworms to remove contaminants from soil. Earthworms have the ability to change the physical, chemical, and biological properties of soil, such as nutrient availability, aeration, soil structure, and, consequently, the activity of microbial communities in the soil, since they have been shown to ingest dirt and mix it in their tummies. It is widely acknowledged that organic materials or substrates can undergo biotransformation through a process called mineralization or composting. Vermicomposting is the term for when earthworms help or expedite the natural composting process of organic materials. The biodegradation of organic matter via the interactions of earthworms and microorganisms is known as vermicomposting. Vermiremediation is the term used to describe composting aided by earthworms when the organic matter or substrate is contaminated. In addition to clearing the soil of pollutants, vermicomposting has several other benefits. Firstly, vermicomposting is an environmentally benign and potentially sustainable method of restoration, in contrast to traditional physicochemical methods that need chemical treatment or soil extraction. Furthermore, the metabolic processes of degrader microorganisms and enzymes are always boosted in soil that has been contaminated by organic wastes due to the use of earthworms in the remediation process. In the end, this results in better soil structure and nutrient availability for increased crop yield and plant development. Like other bioremediation techniques, vermiremediation has a lot of drawbacks and difficulties even if it's a perfect way to clear up mildly contaminated soil. First of all, extremely contaminated soil cannot be cleaned with vermiremediation. It should only be used on slightly contaminated or, at most, substantially contaminated soils that don't clearly harm earthworms. Since many birds eat earthworms, vermiremediation may contaminate the food chain and cause contamination.

Phytomanagement

This integrated site management approach seeks to offer benefits to the environment, society, and economy. Besides reducing the risks caused by toxic substances, photomanagement encourages the use of plants that have the ability to perform phytoremediation. The term "phytomanagement" refers to the process of modifying soil-plant systems to influence TE fluxes in the environment in order to restore contaminated soils, recover valuable metals, or raise crop micronutrient concentrations. Any biological, chemical, or physical technology used on a vegetated site is referred to as phyto-management. When plant biomass products are produced, phytomanagement should either be more economically viable than alternative methods for fortification or remediation, or it ought to be cheaper to implement. This could include the production of bioenergy or lumber on contaminated land practices that don't affect the amount of food produced (Robinson *et al*. 2009; Murrels *et al*. 2007) [38, 35].

Bioventing

One method of in-situ environmental cleanup is bioventing. It is predicated on the bioremediation principle, which uses soil microbes to break down harmful pollutants found in the unsaturated zone of soil. Through the controlled stimulation of airflow, oxygen is delivered to the unsaturated (vadose) zone, enhancing the activity of native bacteria and promoting bioremediation. The distinctive feature of bioventing systems is their ability to both volatilize and biodegrade gasoline molecules on the spot. Although soil vapor extraction and bioventing use the same equipment, their working principles are very different. Soil vapour extraction, or SVE, maximizes volatile organic compound volatilization through vapour extraction, in contrast to bioventing, which depends on boosting the microbial degradation process at the vadose zone by moderate air injection.(Ozkara *et al*. 2019) [36]. Bioventing can be used to treat any component that is aerobically biodegradable. Specifically, bioventing has shown to be highly successful in cleaning up spills of petroleum products, such as diesel, kerosene, gasoline, and jet fuel. The amount of moisture in the soil is crucial to the bioventing process. Bioventing efficacy is decreased by high soil moisture content or limited soil permeability. The healing process may be slowed by low temperatures. Maintaining appropriate air flow rates becomes crucial in conjunction with this.

Organic farming method

It constitutes one of the most significant technical advancements that has just begun to proliferate over the globe, particularly in industrialized nations. Its goal is to shield agricultural output and soil from the risks of pollution brought on by chemical use (pesticides and fertilizers). (Aichner *et al*. 2013) [3]. The goal of organic agriculture is to produce clean, safe food for human consumption while preserving the natural qualities of the land and preventing its degradation. This is achieved by avoiding the use of chemicals in agricultural practices. It also protects the surroundings. The following are three unique results of organic agriculture:

The first effect is a rise in agricultural production and productivity (supply side).

The second result is that it produces an agricultural product that each individual consumer (the demand side) finds acceptable.

The third effect is that it protects agricultural soil and its constituent parts from deterioration and decrease while also improving the surrounding environment. (Al-taai *et al*. 2021) [7].

Organic farming is based on two primary axes

The first is that artificial pesticides and fertilizers have no place in agriculture. Instead, biological and organic fertilizers can be used to achieve this. Using crop leftovers and animal waste on the one hand, and utilizing legumes and organic waste on the farm, is how this process is carried out. It is based on the agricultural cycle of crop rotation. The chemical, natural, and biological qualities of the soil are enhanced by these organic and biological fertilizers, and the result is an increase in crop yield and output. Additionally, it makes agricultural soil more resilient to certain innate plant diseases. Additionally, by using less chemical pesticides and fertilizers, it lowers the expenses related to growing agricultural crops.

The second: Using safe control techniques that effectively eradicate pests, organic agriculture exemplifies the safe disposal of pathogenic pests. It also doesn't have any negative impact on people, pets, plants, or agricultural soil. This sentence depends on numerous techniques. The most popular techniques are as follows:

a) The application of microbial pesticides, or biological insecticides based on fungi, bacteria, and viruses.
b) The application of genetic engineering technologies to the control of pests by creating plant subspecies or varieties resistant to different pests and illnesses.
c) It is imperative to utilize dietary inhibitors. These are substances that, rather than repelling or killing the insect, stop it from feeding, which ultimately causes it to perish. It also doesn't have any negative side effects.
d) Using resources that are attractive and insect repellents; enticing elements, such as pheromones, force insects into certain traps where they can be gathered and removed. Insects do not find repellents to be friendly or poisonous. When used, it keeps insects out of crops that have been cultivated.
e) Instead of using insecticides to combat dangerous insects, natural pest control methods should be employed. (Fadlallah *et al*. 2010) [19].

Physical methods of soil pollution prevention

Soil vapour extraction

Chemicals from the soil's vadose zone in a subterranean environment can be extracted physically using a technique called soil vapor extraction (SVE). It is an effective technique for cleaning up soils contaminated by volatile or semi-volatile organic chemicals found in the unsaturated zone of the soil, such as xylene, toluene, benzene, ethylbenzene, and petroleum range hydrocarbons (PROs and DROs). (Sunil *et al*. 2023) [48]. The method involves applying a vacuum to the soil, which creates an airflow through the soil matrix and moves the contaminants to extraction wells and air treatment units before they are released into the atmosphere. When a pressure gradient is created, gas flow and airflow in the unsaturated zone which is generated by Henry's Law constant >0.01 or vapour pressure > 0.5 mm Hg can be utilized to remediate pollutants. Four distinct procedures control the cleaning process in the SVE system. They are as follows:

1. **Volatilization:** In the soil vapour extraction system, this is the main process. When soil air travels through the pollutants on the surface of the particles, it turns to vapor, that is then gathered via extraction wells.
2. **Advection:** A pressure gradient is produced inside the vadose zone when a vacuum is applied to it. Consequently, the pollutants found in the vadose zone begin to migrate in the direction of the extraction well.
3. **Diffusion:** This is the process by which a material disperses or "diffuses" into its surroundings. The extraction wells create a negative concentration gradient that leads to diffusion, which causes the contaminants with higher concentrations to move toward the wells with lower or no amounts of contaminants.
4. **Desorption:** It is the process of removing impurities from the soil's surface. Because of a concentration gradient in the soil, when vacuum is applied to the system, the soil-air is drawn from the soil's surface and travels via the empty spaces between the soil particles and towards the extraction wells.(Sunil *et al*. 2023) [48].

Vitrification

Vitrification is the broad term for the process of turning a material into glass. One way to achieve this would be to quickly cool a material that has been heated to an extremely high temperature. The process of vitrifying soil involves applying heat to polluted soil in order to melt it and turn it into a crystalline or glassy substance that stops future leaks. The temperature of the soil is raised to between 1600 and 2000ºC (2900-3000ºF). It works well with soils that contain wastes such as radioactive material, hydroxide, carbonates, and silicates; it also works well with incinerator ash or off-gas liquor. Because organic trash becomes inert at high temperatures, it works especially well for it. It is a technique that can be applied both in-situ and ex-situ. (Well *et al*. 2017) [49].

In-situ vitrification (ISV)

It involves heating and melting dirt, sludge, or sediments using electrical power. It uses an electrode system made of graphite with a diameter of 5 cm that is buried 60 meters to create a square edge of one meter.The electrode is subjected to an electric current, which causes the soil to overheat. The molten material is then cooled, creating a vitrified surface. When power is supplied, the melting keeps going downhill and outward at a rate of 4 to 6 tons per hour, or 1 to 2 inches per hour. As the melt moves closer to the designated treatment depth, the electrode array is gradually decreased. A vitrified monolith with a glass and microcrystalline structure remains after cooling. This monolith can withstand weathering since it is incredibly robust.

Ex-situ vitrification (ESV)

Ex-situ vitrification is a method used to treat polluted soil in certain reactors. The concept of in-situ vitrification is related. The difference is that the garbage needs to be excavated before it can be treated. The polluted dirt is heated and turned vitrified by being placed inside a furnace. Electric arch furnaces and plasma torches are examples of heating devices. trash soil is fed into a rolling furnace in plasma torch technology, where centrifugal forces keep the trash and the molten material pressed against one another. The trash rotates through plasma that is produced by a stationary burner. The molten material is removed from the furnace by slowing down the hearth's rotation, and the slag escapes via the bottom hole. Carbon electrodes, cooled sidewalls, a continuous feed system, and an off-gas purification equipment are all part of an arc furnace system. The waste is fed into a chamber that is heated to temperatures more than 1500 degrees Celsius. As the melt leaves the vitrification unit and cools to form a glassy solid, inorganics become immobile. (Khasanova *et al*. 2023) [28]

Some alternative ways for curbing soil pollution

1. **Numerous farming and forestry techniques can be used to reduce soil erosion. Ex:** Tree planting on bare hillsides. Shifting cultivation can be replaced with contour cultivation and strip cropping. It is possible to develop diversion canals and terracing. Reducing deforestation and using animal dung in place of chemical manures helps stop soil erosion over time.
2. **Manufacturing of organic fertilizers:** Toxic chemical pesticides ought to be replaced by biopesticides. Chemical fertilizers that are synthesized ought to be replaced with organic fertilizers. To make compost manure, for example, organic wastes from animal dung can be employed instead of being thrown away carelessly and contaminating the land.
3. **Public awareness:** To inform people about health risks associated with environmental education, both official and informal public awareness programs should be implemented.
4. **Recycling and Reusing Waste Materials:** Recycling and reusing materials including paper, plastics, metals, glassware, organic materials, petroleum products, and industrial effluents can help reduce soil contamination. (Khasanova *et al*. 2023) [28].
5. **Toxic chemical ban:** Chemicals and pesticides that are lethal to both plants and animals, such as DDT and BHC, should be outlawed. It should be illegal to demolish nuclear reactors or dispose of radioactive material improperly.
6. **Appropriate treatment of solid waste:** Before being released into the environment, solid waste must be appropriately disposed of by being treated. For instance, garbage that is acidic or alkaline can be neutralized before being disposed away to prevent contaminating the soil. It is also recommended that biodegradable trash be broken down in a controlled environment prior to release into the surrounding environment.

The zero-pollution action plan

By 2030, the zero-pollution action plan aims to reduce chemical pesticide use and associated risks by 50%, as well as the use of more dangerous pesticides by 50%. Soil pollution can also arise from an excess of nutrients. They are caused by the application of fertiliser and manure or by the deposition of specific air pollutants, and they result in ecosystem eutrophication and decreased biodiversity. By 2030, the excessive nutrient application-related nutrient losses are to be reduced by at least 50%, according to the zero-pollution action plan. Reducing the area of land affected by air pollution by 25% is another aim that will encourage better soils; this target is evaluated in the section on air and ecosystems. The zero-pollution aim, which states that soil contamination should be so low by 2050 that it no longer endangers human health, is reaffirmed in the EU's 2030 soil strategy. The zero-pollution hierarchy is in line with the plan, which places a high priority on stopping pollution at its source. The soil strategy calls for the creation of a future soil health law that is anticipated to contain guidelines for locating, cataloguing, and cleaning up polluted locations in order to drastically lower risks. (Khasanova *et al*. 2023) [28].

Conclusion

One form of environmental pollution that comes in many forms is soil pollution, which includes soil pollution from agriculture, pollution from industry, and pollution from urbanization. These various forms of soil contamination will deplete the soil's mineral content and decrease its fertility. By adopting some extreme steps, such as promoting the use of organic manures and biofertilizers, processing industrial waste before disposal to remove toxins, treating landfills, and reusing plastics, soil pollution can be avoided. In order to stop soil erosion, reforestation should be promoted. It is time to outlaw the use of pesticides, insecticides, and hazardous fertilizers. Crop rotation, organic farming, holistic pest control, and other sustainable agricultural techniques should be used. Techniques for repair and remediation should be applied to raise the caliber of the contaminated soil. While myco-remediation utilizes fungi to extract heavy metal contamination, bioremediation approaches use microorganisms to destroy pollutants. Thermal remediation includes heating the soil to increase the amount of volatile harmful chemicals, while phytoremediation employs plants to absorb contaminants. Soil washing and electro-kinetic remediation are two more procedures that may be used, depending on the severity of the soil contamination. In certain situations, this procedure can be used even if the excavation and transportation of contaminated soils to isolated and uninhabited areas appear to be challenging and time-consuming. Governmental organizations, academic institutions, and environmentalists should launch campaigns, education initiatives, and awareness campaigns to raise public awareness of the causes and effects of soil pollution, put into action practical soil conservation strategies, and disseminate knowledge about sustainable practices

Declaration of Competing interest

We do not have any known conflict of interest in publication of this paper.

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