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Review

Geogenic Contaminants in Groundwater: Impacts on Irrigated Fruit Orchard Health

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Abstract

Geogenic contamination of groundwater presents a substantial threat to the enduring production and sustainability of irrigated fruit orchards, especially in arid and semi-arid regions where over 60% of horticultural irrigation depends on groundwater sources. Groundwater quality is increasingly threatened by geogenic contamination, presenting a critical global issue. Geogenic contaminants, such as fluoride and arsenic, combined with agricultural practices and inadequate wastewater treatment, pose a significant threat to groundwater. Concentrations of elements including arsenic, fluoride, boron, iron, and sodium often exceed acceptable thresholds. For instance, arsenic (As) levels up to 0.5 ppm have been reported in parts of South Asia, far exceeding the WHO guidelines limit of 0.01 mg/L. Boron concentrations above 2.0 ppm and fluoride concentrations exceeding 1.5 ppm are prevalent in impacted aquifers. Pollution consequences are far reaching, impacting agricultural ecosystems and human health as polluted water infiltrates the food chain via irrigation. These challenges are compounded by climate change and water scarcity, which further strain water sources, including those used in agriculture. Addressing groundwater contamination requires a multi-faceted approach. Strategies include developing crops that can tolerate toxicants, improving irrigation techniques, and employing advanced wastewater treatment technologies. This study solidifies current knowledge concerning the uptake processes and physiological effects of various pollutants in fruit crops. This review emphasizes the synergistic toxicity of many pollutants, identifies gaps in knowledge in species-specific tolerance, and emphasizes the dearth of comprehensive mitigating frameworks. Potential solutions, such as salt-tolerant rootstocks, gypsum amendments, and alternative irrigation timing, are examined to enhance resilient orchard systems in geogenically challenged areas.

Keywords: contaminants; fruits; geogenic groundwater; mitigation; pollution; water management

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1. Introduction

Groundwater, the hidden resource under our feet that was once thought to be an untouchable supply of water necessary for life, is currently under increasing threat [1]. The vadose zone is a layer of unsaturated soil above the groundwater table that acts as a natural barrier to protect groundwater from contamination [2,3]. Geogenic contamination arises from the natural presence and mobilization of harmful substances within the environment [4]. These pollutants include a broad spectrum of substances, such as organic and inorganic compounds, radioactive elements, biological agents, and physical contaminants that alter the water's taste and clarity [5]. A complex mixture of contaminants seeps into the earth as a result of our actions on the surface, upsetting the fragile equilibrium of the underground environment [6]. Additionally, geogenic pollution stemming from naturally high levels of elements like arsenic and fluoride in rock formations poses a serious threat [7].

Groundwater contamination has extremely negative consequences. The water's microbiological and physical safety is suddenly jeopardized [8]. Through irrigation, this tainted water can move up the food chain and endanger the health of people who eat the produce grown with it [9]. Moreover, certain contaminants may be detrimental to crops, lowering crop yields and endangering agricultural ecosystems' overall health [10]. Although groundwater is an essential resource for drinking water and irrigation, there are rising concerns. Agriculture, the primary consumer of freshwater (roughly 70%), is followed by industry and domestic uses [11]. Interestingly, groundwater supplies a quarter of all irrigation water and half of the domestic freshwater needs. However, the nature of water pollution evolves with development. Richer nations suffer from agricultural runoff, whereas low-income countries contend with inadequate wastewater treatment, resulting in poor water quality [12]. Unfortunately, it is challenging to evaluate the condition as a whole due to the lack of thorough data on water quality [13]. Although agriculture makes up the majority of India's income, the country also has particular problems with groundwater pollution. The most common issue is high fluoride levels, especially in areas like Uttar Pradesh, Tamil Nadu, Andra Pradesh, Rajasthan, and Gujarat [14]. There is a risk to public health in this instance because an estimated 66 million people are anticipated to drink water with fluoride levels over the allowed limits. Due to its carcinogenic properties, arsenic may pose a serious risk to human health. Some freshly identified poisons, like pesticides, fertilizers, and genetically engineered foods, are causing new concerns even though their production levels have dropped [15]. These pollutants, originating from industries, farms, and households, readily enter the water cycle and potentially contaminate the irrigation water [16,17]. This increases the risk level related to crop uptake and human health. Studies reveal pharmaceuticals and antimicrobials can be absorbed by the crop through irrigation water [18]. These contaminants' versatility makes the nature of their effects uncertain. Frequently applied as soil amendments in irrigated areas, manure and biosolids can also contribute to organic micro-contaminants detrimental to crops [19]. The problem is made more difficult by water scarcity and climate change. Reclaimed water becomes an alluring alternative when dependable water sources become harder to come by, particularly in arid areas. However, due to their longevity in the environment, medications and personal care products may be present in trace amounts in this water, which could cause long-term concerns [20].

In peri-urban areas, the combined effects of soil additives, air deposition, and trace elements from reclaimed water can drastically lower agricultural yields [21]. Food safety concerns are raised due to the bioavailability of contaminants in crops [22]. This is a crucial mechanism of causing harm to crops, as per our understanding. Nitrogen uptake and photosynthetic activities might be affected and can also cause other effects such as stunted growth and reduced yields [23]. Damaging plant cells or changing the hormonal balance can occur due to pollutants that adversely affect growth and reproduction. The severity of these effects can be determined by the kind of contamination, plant species, soil makeup, and irrigation methods.

By acknowledging the threat posed by new contaminants and their potential consequences on crop health and food safety, we may develop mitigation strategies [24]. These include developing new crop varieties that are resistant to pollutants, simplifying irrigation methods to reduce the number of pollutants people are exposed to, and treating wastewater using different methods to eliminate pollutants before it is used for irrigation. Implementing such a comprehensive plan might ensure both the sustainability of agricultural activities and the quality of our food supply [25–28].

Water-related conflicts highlight the vulnerabilities of water infrastructure and the potential use of water contamination as a weapon [29]. Despite progress on Sustainable Development Goal 6 (SDG 6), which seeks to guarantee everyone's access to clean water and sanitation, significant challenges remain. It is challenging to assess progress toward the majority of the SDG 6 targets due to insufficient reporting and monitoring. The global scarcity of clean drinking water in 2022 disproportionately impacted rural areas, impacting billions of people [30]. Conversely, irrigation has mainly been credited with driving up agricultural productivity and spurring economic prosperity [31]. Although irrigation is essential for the best possible fruit growth, there may be unforeseen repercussions. Common irrigation water sources like groundwater may naturally include heavy metals, arsenic, and fluoride, among other geogenic pollutants [32]. Fruit orchards may be at risk even though these toxic chemicals are only present in minimal concentrations due to irrigation techniques that concentrate them in the soil [33]. While numerous studies have assessed geogenic pollutants in groundwater and their effects on general agriculture, a focused synthesis on irrigated fruit orchards remains absent. Given their perennial nature and extensive root systems, fruit crops respond differently to geochemical stressors than annual or biennial crops. This review focuses on an integrative analysis linking groundwater chemistry to orchard health by drawing on insights from both geosciences and horticulture. Key focal points include the following: (i) mechanisms of geogenic contaminant uptake and accumulation in fruit trees; (ii) sub-lethal and cumulative impacts on yield and fruit quality; (iii) species- and cultivar-specific responses; and (iv) critical knowledge gaps and mitigation strategies for sustainable orchard management under contaminated irrigation regimes.

2. Occurrence and Sources of Geogenic Contaminants

Hazardous elements that naturally occur in groundwater are referred to as "geogenic contamination". An aquifer is a subterranean layer that retains water, and it is made up of rocks and minerals that interact with the groundwater itself to cause contamination. These reactions may release a variety of pollutants into the water, including fluoride, heavy metals, and arsenic [34]. Geogenic pollution poses different difficulties than anthropogenic contamination brought on by human activity. Finding alternate water sources or treatment techniques, as well as identifying regions with a high risk of geogenic contamination, are essential first stages in reducing these risks. Identifying areas with high geogenic contamination risk and finding alternative water sources or treatment methods becomes a crucial step in mitigating these threats [35].

2.1. Types of Geogenic Contaminants

Numerous contaminants are present in both soil and plants. Table 1 details the concentrations of various geogenic contaminants in the soil and their potential accumulation in fruit crops. Table 2 provides specific concentrations of geogenic contaminants found in the soil of fruit orchards. Table 3 provides the information related to country specific geogenic contamination.

2.1.1. Arsenic

A naturally large proportion of traces of arsenic present in rock, soil, water, and air is found in the Earth's crust [36]. Rock, soil, water, and air all contain trace amounts of arsenic, which is found in large amounts in the Earth's crust within nature [37]. Its normal concentration in the continental crust is 1–2 mg/kg; mean concentrations in igneous rock range from 1.5to 3.0 mg/kg, whereas in sedimentary rock they vary from 1.7 to 400 mg/kg [38]. In some areas, natural geological processes lead to the pollution of drinking water with arsenic, which can be harmful to human health. Arsenic is distributed and transported through the ecosystem in a complicated way, constantly cycling via the soil, water, and air [39]. Leaching and runoff occur once it is introduced into soil and groundwater via the weathering of rocks, and it may also emanate from human sources [40]. Inorganic arsenic is typically found in groundwater as arsenate and arsenite, with oxidation-reduction processes mediating the interconversion between the two forms [41].

2.1.2. Fluoride

Fluorine has a high electronegative potential and is the lightest halogen element [42]. Various solute complexes can be formed by combination with different cations, resulting in fluoride formation [43]. The continental crust has an average concentration of fluoride of about 611 mg/kg, although different types of rock have variable values [44]. Fluoride-containing minerals dissolving in aquifer materials is a common cause of fluoride pollution [45]. Skeletal and dental fluorosis occurs due to the consumption of fluoride in large amounts [46]. The major constituents of fluoride are found in minerals such as fluorite, apatite, cryolite, and topaz. Since 1937, chronic fluorosis has resulted from widespread geogenic fluoride poisoning of groundwater in India, a country with considerable crustal fluoride deposits [47]. Generally speaking, phosphatic fertilizers, soil, plants, and rock minerals contain fluoride.

2.1.3. Salinity

Salinity is referred to as the concentration of dissolved particles and ions in water. It varies greatly according to geographical region [48]. Dissolved solids such as gypsum, carbonates, anhydrite, halite, fluoride salts, and sulfate salts raise the salinity levels in groundwater [49]. Salinity has several significant contributors involving chloride (Cl^-), sodium (Na^+), nitrate (NO_2^-), calcium (Ca^{2+}), magnesium (Mg^{2+}), bicarbonate (HCO^{3-}), and sulfate (SO_4^{2-}), with local variations in concentrations of boron (B), bromide (Br), iron (Fe), and other trace ions [50].

2.1.4. Iron and Manganese

Iron is abundantly present in the Earth's crust, so the majority of water contains a small amount of it [51]. Iron and manganese naturally occur in rocks and can leach into groundwater. Elevated concentrations of these elements can affect water taste and color. Igneous rock minerals with relatively high iron content include pyroxenes, amphiboles, biotite, magnetite, and olivine. Iron's availability in solutions is influenced by environmental conditions, especially changes in oxidation-reduction reactions [50]. Under reducing conditions, ferrous polysulfides like pyrite and marcasite may form, while oxidizing environments lead to the precipitation of ferric oxides or oxyhydroxides such as hematite and goethite [52].

2.1.5. Uranium

With an average concentration of 0.0003% in the Earth's crust, uranium is a radioactive metal generally obtained in some aquifers. The important minerals found in uranium ore are uraninite (UO2), pitchblende (U3O8), and davidite (Fe, Ce, U)2(Ti, Fe, V, Cr)5O12 [53]. Due to its high density and pyrophoric qualities, a reduced level of uranium residue—which contains approximately 0.2% 235U—is utilized in armor-piercing shells and counterweights [54]. Even though uranium has low radiotoxicity, chemical toxicity should be considered. While uranium's radiotoxicity is low, its chemical toxicity should not be disregarded, especially in its dissolved form as the uranyl ion [55].

2.1.6. Radon

Radon is a naturally occurring radioactive gas that can dissolve in groundwater. It is produced by the radioactive decay of radium-226 found in uranium ores, phosphate rock, and various rocks like granite, gneiss, and schist [56]. Not all granitic locations release large quantities of radon, even though it is present in limestone to a lesser extent [57]. Since radon is a gas, it may easily travel through soils and faults and build up in enclosed areas like caverns or water. Because of its short half-life (3.8 days for 222Rn), the concentration drops off quickly as one moves farther away from the source [58].

2.1.7. Strontium

Strontium contamination can arise from the weathering of rocks. Strontium, a soft alkaline earth metal, occurs naturally in combination with other elements and compounds due to its high reactivity to air [59]. Celestite (SrSO4) and strontianite (SrCO3) are common strontium minerals found in nature. Water-insoluble strontium compounds can become soluble through chemical reactions, posing greater health risks. Fortunately, strontium concentrations in drinking water are typically low [60].

2.1.8. Selenium and Chromium

Trace elements like chromium and selenium have the potential to become geogenic pollutants [61]. Chromium, the 21st most abundant element in the Earth's crust, appears in several oxidation states, with trivalent chromium being the most stable [62]. While volcanic eruptions and the erosion of rocks that contain chromium are the reasons why chromium compounds are present in the environment, hexavalent chromium (chromate) is primarily produced from different sources [63]. Selenium and chromium concentrations vary in soil, seawater, and rivers, with different oxidation states exhibiting varying stability and toxicity levels [64].

3. Uptake and Accumulation in Crops

There are different ways that contaminants enter groundwater, such as seepage from the surface or shallow subsurface, direct entry from wells, cross-contamination of wells that access various aquifers, and pumping-induced flow of dirty water into freshwater aquifers. Furthermore, groundwater and geological strata may interact with naturally occurring contaminants like radon and arsenic. The types of rocks and soils, temperature, pressure, and hydrogeochemical processes influenced by soil solubility are some of the factors that affect groundwater quality [65–73]. The primary mechanisms regulating the chemistry of groundwater in an aquifer involve hydrogeochemical processes and water–sediment interactions, which include adsorption, cation exchange, oxidation-reduction reactions, hydrolysis, and more [5].

The ability of various kinds of plants to absorb and accumulate toxic chemicals from the soil may differ. By developing root hairs, plants act as tiny filters for organic contaminants, absorbing them along with water [74]. Then, as seen in Figure 1, these pollutants move through two pathways within the plant: one that connects cells (like cars on a freeway) and another that goes through the cells themselves (like taking a side road). Once inside the plant, these pollutants may go through several pathways within its internal network, build up in the roots, or reach the shoots [75]. Methods for precisely measuring the quantity of pollution absorbed by a plant are still being refined by scientists. Even though conventional methods depend on calculations based on water flow, upcoming approaches appraise the defined properties of each pollutant to give a more specific evaluation of it [76].

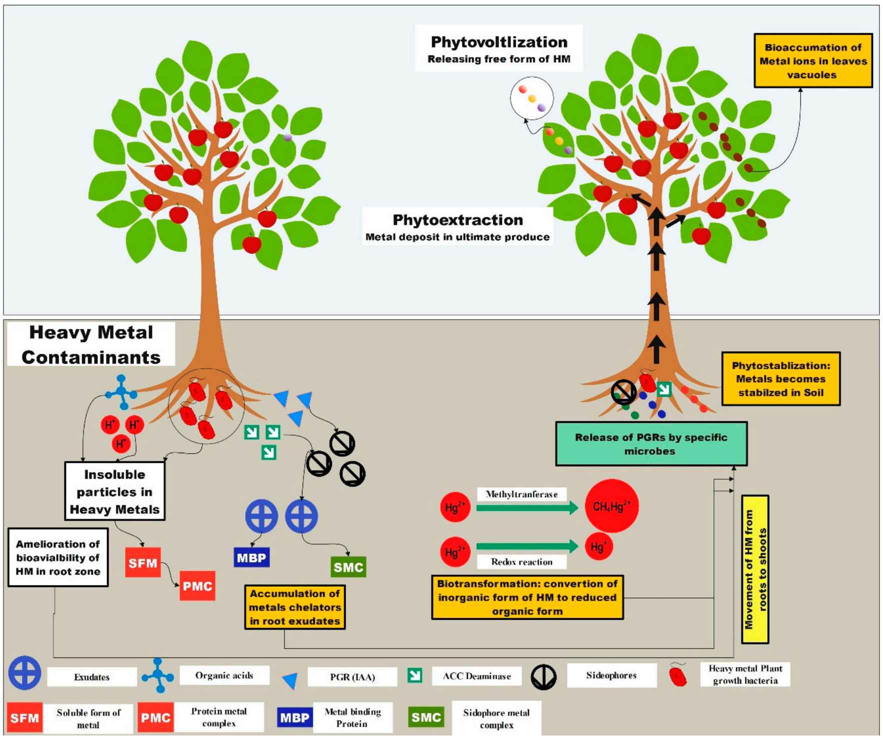

Figure 1. Procedure through which HMT-PGP (heavy-metal-tolerant–plant-growth-promoting) microorganisms and plants interact to remediate soil contaminated with heavy metals. Different arrow in upwards direction shows the movement of PGR released by the Microbes and different dots represent the production of different PGR by the microbes

Notably, enzymes are essential for plants to break down harmful substances such as animal livers produced during detoxification [77]. The "green livers" theory describes how plants can detoxify pollutants like CEC through these enzyme-mediated processes [78]. Certain pollutants have the potential to be lipophilic, meaning they can enter and move through plant tissues. Phases I, II, and III are the three stages of enzyme-facilitated chemical changes that follow absorption. Reactive group participation occurs in phase I, which results in the hydrolysis and redox-based conversion of pollutants into metabolites. Metabolite conjugation with substances such as glutathione, carbohydrates, or amino acids takes place in phase II. Phase III concludes with the preservation of metabolites that are incapable of undergoing further transformation, either incorporated into cell walls or in vacuoles [79–81]. These three metabolic phases—I, II, and III—are crucial since plants lack an excretory system [82].

Geogenic contaminants such as As, F^-, B, Fe, Mn, Pb, and Cd can move in fruit crops with the help of irrigation with groundwater. Their uptake and accumulation depend on variable factors like element speciation, nature of the soil, root architecture, and plant species. Various contaminants, namely fluoride and arsenate, are absorbed with water during transpiration via passive mass flow or diffusion into root cells, especially under high transpiration rates. Active transport via membrane transporters can also help to move contaminants into fruit crops; for instance, as arsenite (AsO_3^{3-}) moves into fruit crops by entering through aquaporins, Cd, Pb, and Ni enter via metal transporters such as ZIP (Zrt/Irt-like proteins), NRAMPs, and calcium channels due to ionic mimicry. There are also other methods like ion exchange and chelation in the rhizosphere water flux, ion mobility, binding affinity with ligands (e.g., phytochelatins, metallothioneins), storage and detoxification sites, and vacuoles.

Factors Influencing Uptake Rates

Numerical parameters, including soil pH, temperature, and moisture levels, can influence contaminant availability, while soil-dwelling organisms can affect nutrient availability and uptake by plants [83]. The solubility, mobility, and chemical form of contaminants play an important role in their uptake by plants, which, in certain civilizations around the world, has been effectively applied for centuries in plant-based bioremediation of metal-contaminated soils [84]. These pollutants are significant threats to environmental compartments like soil because they are frequently released as waste. Because of processes including volatilization, microbial degradation, and photodegradation, as well as external factors such as air currents, surface runoff, and soil erosion, their destiny in the soil is unpredictable [7].

Concerns extend beyond environmental impacts to potential effects on the terrestrial food chain, highlighting the necessity of understanding their uptake and impact on plants, the primary producers [85]. The process by which groundwater with geogenic contaminants decreases the overall efficiency of plants and pollutants are taken in by plants from the soil is shown in Figure 2.

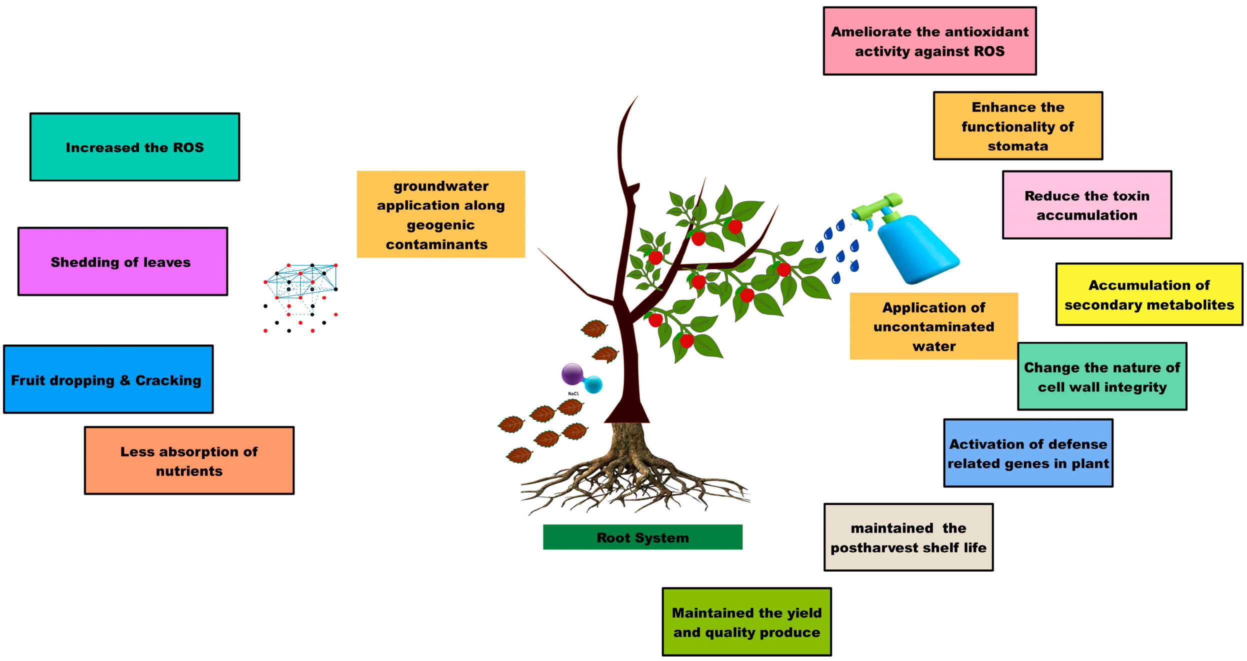

Figure 2. Effect of geogenic contaminants and uncontaminated water on the physiological aspects of fruit crops.

One study shows that some contaminants, which are affected by factors such as temperature, interaction between microbes, type of plant species, pollutant type, and soil erosion, accumulate more in plant roots than in aerial portions [86]. Soil has an essential component, humic acids, which play an important role in the assimilation of pollutants [87].

Geogenic contaminants of the soil affect the bioaccumulation of pollutants, as an alkaline environment promotes microbial breakdown and a high pH environment boosts the absorption into soil particles [88]. Several soil elements, including colloidal clays along with elements like hydraulic conductivity, age, mobility, and the presence of divalent ions, foster the uptake of contaminants by plants [89]. While climatic change might influence the clearance of toxic chemicals from the soil through photodegradation, which could lead to the creation of more hazardous metabolites, air pollutants can be deposited on plant foliage, particularly in urban areas [90,91]. To improve crop resilience and reduce pollutant uptake, researchers are investigating cutting-edge techniques like controlled environment horticulture, nanomaterials, exogenous phytohormones, and helpful microbial endophytes [92].

4. Effects on Plant Physiology and Yield of Fruit Crops

Fruit crops are directly exposed to soil and water throughout their growth, making them particularly susceptible to geogenic contaminants [93]. Table 4 highlights numerous instances of fruits contaminated with heavy metals. Exposure to arsenic (As) typically starts in the plant's root tissues, where it prevents the plant from growing and developing further [94]. Eventually, this leads to plant mortality since it obstructs vital metabolic processes like oxidative phosphorylation and ATP synthesis at high enough concentrations [95]. Furthermore, transfer to the shoot has the potential to severely hinder plant development and productivity [96]. As contamination, which can build up in their tissues, poses a risk to tomatoes, a major horticultural crop in Europe and the US. As a result, consuming any edible portion of As-contaminated tomatoes puts humans at risk of consuming it through the food chain. Compared to natural sources like volcanic eruptions, forest fires, and the wind carrying soil particles, human activities such as mining, processing metals and ore, farming, and the disposal of metal-contaminated waste such as wastewater and sludge can release three to ten times more Cd into the air [97]. Cadmium has several negative effects on plants, such as poor uptake of water and nutrients, inhibition of both promoting and inhibitory enzymes, metabolic disturbance, elevated levels of reactive oxygen species (ROS), increased lipid peroxidation, and changed expression of genes and proteins [98].

In general, both aquatic and higher plants tend to accumulate mercury (Hg). This can occur in different forms, such as HgS, Hg^{2+}, Hg0, and methyl-Hg [99]. It has been discovered that high Hg^{2+} concentrations are extremely harmful to plant cells, resulting in both apparent damage and physiological problems, including the closing of leaf stomata and the actual physical obstruction of water flow [42]. By interfering with vital enzymes, lead (Pb) negatively impacts plant morphology, growth, and photosynthetic processes, which hinders seed germination [100]. Additionally, elevated Pb concentrations can induce reactive oxygen species (ROS) in plants, which can lead to oxidative stress [101]. Similar morphological and physiological changes are seen in plants exposed to high Cr levels because of increased ROS generation [102–104]. Through oxidative processes such as lipid peroxidation, oxidative protein degradation, inhibition of DNA and RNA damage, and other mechanisms, excessive generation of ROS can result in cell death [41]. Numerous investigations have demonstrated that Cr poisoning causes chromosomal abnormalities in plant tissues, as well as disruptions in the regulation and function of many proteins [105,106].

5. Human Health Implications: Transfer of Contaminants from Crops to Humans

Heavy metals, such as cadmium, lead, and arsenic, are potent sources of contamination known to produce neurological disorders, kidney damage, and cancer [107,108]. Well below the dangerous levels, these metals pose a serious threat when found in food, water bodies, or soils because they enter the food chain and accumulate, later being absorbed into the human body [109]. Figure 3 elaborates on the biochemical and physiological properties of food crops, showing just how far-reaching the unlucky effects might be due to these contaminants [110,111].

Figure 3. Health risks, fate, mechanisms, and management.

Chronic lead exposure results in developmental delays, learning disabilities, and behavioral problems. Apart from neurological damage, high blood pressure, renal damage, and reproductive system toxicity have been exposed as the effects associated with lead-exposed people [112,113]. Cadmium is a highly toxic heavy metal that affects the kidneys and the skeletal structure primarily. Chronic cadmium exposure, mainly through contaminated food and tobacco smoke, may lead to impotence, osteoporosis and brittle bones with frequently occurring fractures, and critically severe inhibition of renal function [114,115]. Also, several pesticides have been classified by the International Agency for Research on Cancer as carcinogenic [114,116]. The widely applied herbicide glyphosate and the organophosphate pesticide chlorpyrifos are reputed probable or possible carcinogens based on evidence from animal studies and epidemiological data. Pesticides are neurotoxic chemicals that affect both the body and the central nervous system [117]. Examples of potentially lethal insecticides include organophosphate and carbamate compounds, which can cause acute symptoms such as headaches, dizziness, nausea, and respiratory distress, with death occurring in severe cases [118–120]. Importantly, pesticides are anthropogenic contaminants, originating from human activities, and are not classified as geogenic pollutants.

Table 1. Concentrations of various geogenic contaminants in soil and water as per various research studies.

Heavy Metal	Typical Concentration in Water (mg/L)	WHO Limit in Water (ppm)	Typical Concentration in Soil (ppm)	WHO Limit in Soil (ppm)	Typical Uptake in Fruit Plants (ppm Dry Weight)	Ref.
Pb	0.005–0.05	0.01 (WHO), 0.05 (NEQS)	10–70	50	0.2–3.5	[21,52,111,121–125]
Cd	0.001–0.01	0.003 (WHO), 0.01 (NEQS)	0.1–1.0	0.02	0.01–0.5	
As	0.001–0.05	0.01 (WHO), 0.05 (NEQS)	1–40	10	0.01–2.0	
Chromium Cr	0.01–0.1	0.05 (WHO), 0.1 (NEQS)	5–100	50–100	0.2–5.0	
Ni	0.01–0.2	0.07 (WHO), 0.2 (NEQS)	10–100	75	0.1–3.0	
Zn	0.01–0.5	3.0 (WHO), 5.0 (NEQS)	10–300	200–300	5–100	
Cu	0.01–0.1	2.0 (WHO), 1.0 (NEQS)	10–200	100	5–50	
Fe	0.3–5.0	0.3 (WHO), 1.0 (NEQS)	100–500	300	10–200	
Mn	0.01–0.1	0.4 (WHO), 0.1 (NEQS)	50–1000	200–300	5–100	

Table 2. Concentration of geogenic contaminants in the soil of fruit orchards.

Fruit Crop	Contaminant	Soil Concentration (mg/kg)	Ref.
Apple	Arsenic	2.1–10.5	[52,122]
	Cadmium	0.5–5.2	[110,121]
	Lead	12.3–42.8	[62,112]
	Chromium	3.2–18.9	[38,40,61]
	Mercury	0.3–2.7	[126]
	Selenium	0.1–0.8	[125]
	Uranium	0.5–3.6	[127]
Peach	Arsenic	1.8–8.3	[34,124]
	Cadmium	0.4–4.7	
	Lead	10.5–38.6	
	Chromium	2.8–15.6	
	Mercury	0.2–2.3	
	Selenium	0.08–0.6	
	Uranium	0.4–3.2	
Citrus	Arsenic	1.5–7.9	[34,128]
	Cadmium	0.3–4.2	
	Lead	9.8–35.4	
	Chromium	2.5–14.3	
	Mercury	0.2–2.1	
	Selenium	0.06–0.5	
	Uranium	0.3–2.8	

Table 3. List of countries with high geogenic contamination.

Country	Contaminant	Discussion	Ref.
Bangladesh	Arsenic	Bangladesh has faced one of the most severe cases of arsenic contamination in groundwater, affecting millions of people who rely on tube wells for drinking water. The contamination has led to widespread health problems, including arsenicosis and various cancers.	[95,129]
India	Fluoride and arsenic contamination	Groundwater in several regions in India, such as parts of Rajasthan, Punjab, and Bihar, experiences a greater percentage of fluoride and arsenic contamination. This contamination poses significant health risks to millions of people who rely on groundwater for drinking and irrigation.	[14,44,71]
China	Arsenic and fluoride contamination	Several regions in China, including Inner Mongolia, Shanxi, and Henan provinces, experience the maximum amount of arsenic and fluoride contamination in underground water. This contamination has led to many human-related problems, such as arsenicosis and dental fluorosis, among local populations.	[34,40,61]
Mexico	Fluoride contamination	Some areas in Mexico, mainly in the central and northern regions, have elevated levels of fluoride in groundwater. This contamination is associated with cases of dental and skeletal fluorosis among the local population.	[34,44]
Osilo Area (Italy)	Geogenic degradation.	The Osilo region exemplifies geogenic deterioration impacting water quality. Scholars have investigated the source, prevalence, influencing factors, and potential remedies for pollutants like ammonium, fluoride, chloride, sulfate, and uranium.	[120]
Iglesiente–Fluminese Mining District, Italy	Geogenic contamination	In this mining district, the quality of water is influenced by both natural geogenic processes and human actions. Scholars have examined the cumulative effects of both geogenic pollutants on water quality.	[61,120]
Southeast Asia	Arsenic and fluoride	These regions face widespread geogenic contamination due to arsenic and fluoride. Millions of people are affected, emphasizing the importance of understanding and addressing geogenic water quality issues.	[40,71]
Cauvery River, India	Geogenic contamination	Quality of river water (Cauvery) and groundwater has been assessed. Both geogenic sources contribute to contamination. Chemical indices differentiate these sources, aiding in understanding water quality dynamics.	[42]
Andes Mountains, South America	Geogenic contamination	Fruit orchards located in high-altitude regions of the Andes Mountains can be susceptible to geogenic contamination, including trace elements and arsenic, in the soil and water, which may be influenced by nearby mining activities.	[95]
Eastern Uttar Pradesh, India	Geogenic contamination	Fruit orchards situated in Eastern Uttar Pradesh, particularly those in proximity to industrial or mining zones, may encounter geogenic contamination challenges, such as elevated concentrations of heavy metals like lead and cadmium in both soil and water sources.	[11]
Mekong Delta, Vietnam	Arsenic	The Mekong Delta, known for its agriculture, including fruit orchards, has faced challenges with geogenic contamination viz., elevated levels of soil arsenic and water. These contaminants can pose risks to fruit crops and consumers.	[61]
Alentejo, Portugal	Arsenic and heavy metals	Alentejo, a prominent region for olive and cork production, has documented issues with geogenic contamination, particularly concerning arsenic and heavy metals in the soil. These contaminants may affect fruit orchards in the region.	[85]
Central Valley, California, USA	Arsenic and selenium	Central Valley is recognized for its agricultural productivity, but it also faces challenges related to geogenic contamination, including heavy	[26]

	metals like arsenic and selenium. These contaminants can originate from natural sources in soil and groundwater.

Table 4. Fruits contaminated with heavy metals.

Fruit	Metal Contaminant	Ref.
Avocado Pear	These heavy metals are typically persistent in the environment, resistant to biodegradation and heat, and thus prone to accumulating to harmful levels. In avocado pear, the levels of cadmium, copper, zinc, iron, lead, nickel, manganese, and cobalt are measured at 0.15, 3.10, 8.87, 28.60, 1.69, 3.34, 1.31, and 1.62 mg/kg, respectively. Source of irrigation: Ground water.	[66]
Orange	The content of cadmium, copper, zinc, iron, lead, nickel, manganese, and cobalt in oranges is 0.10, 0.23, 7.22, 19.0, 5.80, 2.99, 1.09, and 1.67 mg/kg, respectively. Source of irrigation: Ground water.	[34]
Pawpaw	The levels of cadmium, copper, zinc, iron, lead, nickel, manganese, and cobalt in pawpaw are 0.22, 05.29, 07.31, 29.60, 05.57, 05.87, 01.03, and 3.56 mg/kg, respectively. Source of irrigation: Ground water.	[61]
Pineapple	The levels of cadmium, copper, zinc, iron, lead, nickel, manganese, and cobalt in pineapple are 0.08, 0.64, 6.78, 25.70, 4.52, 1.16, 2.60, and 1.43 mg/kg, respectively. Source of irrigation: Ground water.	[130]
Grapes	The presence of heavy metals like lead, cadmium, and arsenic varies depending on the agricultural methods employed and the environmental circumstances. Source of irrigation: Ground water.	[131]
Bananas	Bananas are susceptible to heavy metal contamination, especially cadmium, which can permeate the fruit either from the soil or via the application of fertilizers tainted with pollutants. Source of irrigation: Ground water.	[70]
Oranges	Heavy metals like Cd and Pb can be taken up by crops from soil that is contaminated or through the utilization of tainted agricultural materials. Source of irrigation: Ground water.	[23]
Strawberries	Heavy metals like Cd and Pb, especially when grown in soils with high metal concentrations or exposed to contaminated irrigation water.	[132]
Apples	Heavy metals like lead, cadmium, and arsenic can build up in fruit as a result of contamination in the soil or water. Source of irrigation: Ground water.	[21]
Berries (blueberries, blackberries)	Heavy metals like cadmium and lead can accumulate due to soil contamination or atmospheric deposition. Source of irrigation: Ground water.	[108]
Pineapples	Cadmium and lead, particularly problematic in regions with contaminated soils or where agrochemicals containing heavy metals are used excessively.	[133]
Avocado	Heavy metals like lead and cadmium primarily originate from soil, water, or air pollution, causing contamination. Source of irrigation: Ground water.	[110]
Citrus fruits (oranges, lemons, limes)	Cadmium and lead can be absorbed from contaminated soil or water sources. Source of irrigation: Ground water.	[124]
Peaches	Arsenic and lead, with contamination levels varying depending on soil quality and environmental factors. Source of irrigation: Ground water.	[133]
Mangoes	Cadmium and lead, particularly in regions with contaminated soils or water sources. Source of irrigation: Ground water.	[130]
Pear	Heavy metals like cadmium and lead, especially when grown in soils with high metal concentrations or exposed to contaminated irrigation water.	[131]
Grapes	The presence of heavy metals like cadmium and lead in vineyards can fluctuate depending on factors such as soil composition, vineyard management methods, and environmental conditions. Source of irrigation: Ground water.	[134]

Apricots	When cultivated in areas with polluted soils or water sources, crops have been observed to gather heavy metals like arsenic and lead. Source of irrigation: Ground water.	[131]
Cherries	Heavy metals such as Cd and Pb, which can be absorbed from soil or water sources contaminated with industrial or agricultural runoff. Source of irrigation: Ground water.	[110]
Plums	Heavy metals like Cd and Pb, with contamination levels influenced by soil quality, agricultural practices, and environmental factors.	[70]
Pomegranates:	Cadmium and lead, especially when growing in soils with high metal concentrations or irrigated with contaminated water. Source of irrigation: Ground water.	[121]
Dragon fruit	Plants have the tendency to gather heavy metals like arsenic and lead, especially in areas where the soil or water is contaminated. Source of irrigation: Ground water.	[61]
Papaya	Cadmium and lead can be absorbed from contaminated soil or water sources. Source of irrigation: Ground water.	[66]
Kiwi fruit	Cadmium and lead, especially when grown in soils with elevated metal concentrations or exposed to contaminated irrigation water. Source of irrigation: Ground water.	[130]
Passion fruits	Soil quality and agricultural practices can impact the levels of heavy metals like Cd and Pb found in the environment. Source of irrigation: Ground water.	[130]
Guava	High levels of heavy metals like Cd and Pb, especially in areas with polluted soil or water supplies. Source of irrigation: Ground water.	[73]

6. Regulatory Standards and Guidelines

Heavy metals—lead, cadmium, mercury, and arsenic—are all potential accumulators in crops through either soil pollution, water contamination, or aerial pollutants [134-138]. Long-term exposure to these heavy metals is causative for many health problems that include mainly neurological impairment, renal damage, and cancer [107,135–137]. For this case, various maximum allowable limits of these heavy metals in crops have already been set by different regulatory bodies, including the US EPA, EFSA, and FAO of the United Nations [139]. For instance, EFSA has laid down MRLs for heavy metals in different foodstuffs [139], while the US EPA and European Union (EU) regulations establish MRLs for pesticides in crops based on rigorous risk assessments to ensure consumer safety [140]. Prolonged pesticide exposure is linked to cancers, reproductive disorders, and neurological diseases [141].

Mycotoxins are biologically derived toxic chemicals produced by certain molds that infest crops, particularly grains, nuts, and spices [123]. The intake of such contaminated produce can cause acute poisoning or long-term effects on health, such as liver damage and cancers [142]. Alternatively, they result from biological activity and are influenced by factors such as temperature, humidity, and substrate composition. Therefore, their source is unequivocally biological, justifying their classification as biogenic toxins rather than geogenic pollutants. The World Health Organization, in collaboration with the Food and Agriculture Organization of the United Nations, sets standards and regulations for the permissible levels of mycotoxin in foods [13,31]. As stated, regulations are set with the view that mycotoxin-related health risks for consumers have to be reduced to as low as reasonably possible. The permissible limits of these heavy metals in irrigation water and agricultural produce are recommended by different agencies, including the US Environmental Protection Agency (EPA) and the World Health Organization (WHO) [13,143]. These guidelines will be useful in preventing the excessive build-up of these heavy metals in fruit orchards. High levels of salt in naturally occurring groundwater will lead to soil salinization, and this will affect the growth and yield of fruit orchards during irrigation [128]. There are laws aimed at controlling the extent of soil salinization to reduce adverse effects on crops. Higher levels of nitrate and nitrite in geogenic groundwater are either a natural result of geological processes or from fertilizer use in farming. There are regulatory standards for irrigation water so as not to let the levels of nitrate and nitrite contaminate fruit orchards [28].

7. Mitigation and Management Practices

Water is applied at a time when fruit trees can maintain optimal nutrient balance in the soil, enhance irrigation efficiency, and also reduce erosion of the soil. Through this, water will be well utilized, and fruit yield and quality will be maintained [131,144]. Evapotranspiration is the amount of water loss through plant transpiration and soil evaporation combined. Scheduled irrigation, based on ET demand, will ensure that fruit trees receive adequate watering at the right time, when water is required [120,131]. Many studies have shown that with proper monitoring of soil moisture and lengthening the irrigation intervals according to the ET, it is possible to gain high yields with fruits of high quality [131,145]. This method is efficient and delivers water directly to the root zone of fruit trees. The loss of water through this method is not significant since drip irrigation does not lead to soil erosion, and the applied plant can absorb the nutrients easily.

Implementing alternative water sources can significantly reduce the over-dependency on contaminated groundwater in orchards [131]. Strategies include the adoption of rainwater harvesting systems, utilization of surface water from rivers or reservoirs, and the use of treated wastewater for irrigation purposes. These measures help mitigate reliance on geochemically contaminated water sources [146,147]. There is an overall need for regular monitoring of water quality to pick up any trend of contamination early enough and facilitate prompt intervention measures. Surveillance of the water quality will enable the orchard manager to assess the degree of contamination and make decisions to change irrigation practices accordingly [148]. Application of soil amendments may reduce the uptake of contaminants by fruit trees, as observed by [148]. Phytoremediation of contaminated soils and waters is possible using fruit orchards, with the inclusion of hyperaccumulator plants or vegetative buffer zones [129]. Other strategies, such as liming, adding organic matter, and phosphate application, may alter soil characteristics and hence decrease the bioavailability of toxic elements, that is, heavy metals [149].

Adopting efficient irrigation strategies, such as drip or micro-irrigation techniques, can significantly reduce the volume of water applied, thereby limiting the potential contact of pollutants with the plant root system [150]. Additionally, scheduling water application during periods of minimal evapotranspiration helps prevent increases in contaminant concentration within the soil [144]. A few plant species collect and detoxify these pollutants from soil and water by phytoremediation [129]. Planting hyperaccumulator plants in fruit orchards or using them as vegetative buffer zones around orchards can help in the cleanup of contaminated soils and waters [121]. Several studies have illustrated the different mechanisms behind the remediation of heavy metal-contaminated soil through heavy-metal-tolerant–plant-growth-promoting (HMT-PGP) microbe–plant interaction [96], as shown in Figure 4.

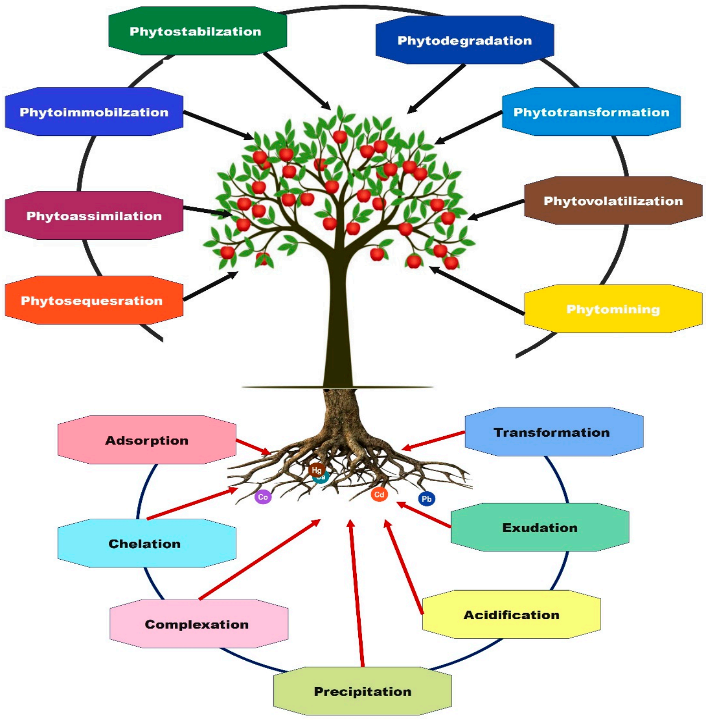

Figure 4. Different steps during phytoremediation. Different round shape near the root zone along with text shows the movement of different geogenic compound to roots

In regions of India, orchards have faced significant challenges due to arsenic-contaminated groundwater, posing threats to both crop production and human health [151]. To address this issue, affected orchard owners collaborated with local political administrations to develop community-based rainwater harvesting systems. These systems supplemented the irrigation that naturally occurred during the dry season from groundwater, thereby reducing the dependency on arsenic-contaminated resources [146]. Lime and gypsum addition raised the pH and reduced the bioavailability of arsenic in orchard soils [149]. The effectiveness of amendments at mitigating arsenic uptake by apple trees was monitored by frequent soil testing [152]. Specifically, arsenic-hyperaccumulating grass species were intercropped with apple plants, and later their foliage was harvested for the removal of arsenic from the soil [121]. Once harvested, such grasses were removed and safely disposed of to prevent their return to the orchard environment. Using this method of intercropping with cover crops tolerant to arsenic showed a reduction in its levels in orchard soils [149]. Figure 4 shows the different steps during phytoremediation. Intercropping with arsenic-tolerant cover crops has shown promise in mitigating arsenic levels in orchard soils.

Efficient water management is crucial for fruit orchards as the performance of fruit trees depends on irrigation, and different species respond differently to it. Deficit irrigation is a technique where water supply is intentionally reduced during specific growth stages to optimize resource use. It ensures efficient water utilization without compromising yield and quality [131]. Evapotranspiration-based scheduling tailors irrigation to the tree's water demand, maintaining high yield and fruit quality [131]. Soil quality is essential for sustainable fruit cultivation. Intensive input use without environmental considerations can lead to soil degradation and salinization [53].

Crop selection and breeding for tolerance in fruit orchards facing geogenic water is a very important aspect of sustainable agriculture. Choosing fruit varieties that have natural drought tolerance is important. Plant breeding programs should look at identifying and propagating such varieties. Landraces, locally adapted traditional varieties, very often possess inherent resilience against water stress. Such landraces can be an important genetic resource [61]. Transgenic studies have attempted to incorporate specific genes into fruit crops that improve their resistance to drought. Increasing the expression of stress-related genes enables the plant to make better use of the available water and thus improves WUE and the response to drought conditions [138]. Major transcription factors include DREB1 and DREB2, which play a critical role in mechanisms of drought tolerance [147]. CRISPR technology enables gene editing with precision. It is now possible to modify fruit trees for improved drought resistance by overexpressing/silencing specific genes [53]. Understanding the signaling pathways involved in the drought response enables the identification of critical genes for modification [53]. A recent review has considered methods related to horticulture, biochemistry, and molecular biology that can enhance the capacity of temperate fruit crops to resist water stress [53].

Remediation of polluted soils in fruit orchards affected by geogenic water contamination plays a crucial role in the protection of health, both in crops and other related ecosystems. Soil pollution can be addressed by many remediation methods. Different tools for remediation of heavy metals in food crops are mentioned in Figure 5.

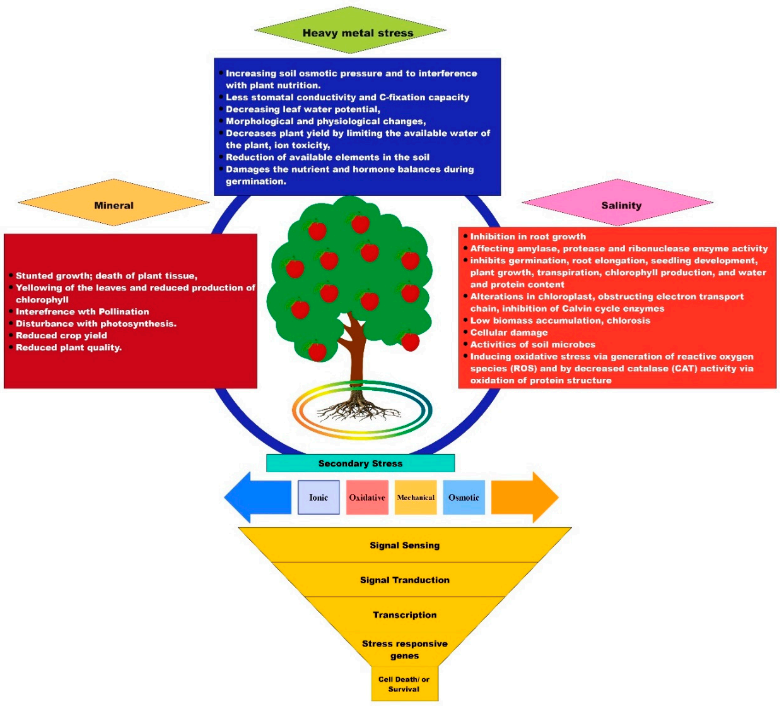

Figure 5. Effect of heavy metals on crop plants.

Some species of plants are capable of absorbing and storing contaminants from the soil in their tissues. In such orchards, some plants can deliberately be planted to absorb pollutants like heavy metals from the soil [121]. Then, these plants are harvested and removed from the site to reduce contamination levels in the soil. This means that this process follows the mechanism that plants take up contaminants, and later on, these contaminants become removed with the plants to clean the soil [153-157]. The remediation of orchards has been effective through the process of phytoremediation using plants to remove contaminants from the soil. Plants that are hyperaccumulators have been found to exhibit high effectiveness and efficiency in metal uptake from the soil [52,107].

8. Future Research Directions

Hyperspectral imaging is an important tool in the valuation of exposure and contamination in fruit orchards affected by geological water impacts. It can project subtle spectral signatures of various contaminants, allowing a detailed assessment of materials that might indicate the presence of pollutants in the soil and water. The assessment comes in handy in that, although hyperspectral imaging can map the sources of pollution and thereby estimate the hot spots of contamination, it gives a spatial distribution of the contaminants with GIS data. In this way, it gives insight into their effects on the ecosystems in different orchards. Moreover, techniques like partial least squares regression can even provide a quantification of contamination levels from hyperspectral data [12].

Adoption of advanced technologies with sustainable practices is characterized as an integrated approach to handling contamination. In the aspect of monitoring, hyperspectral imaging provides continuous monitoring, complemented by other remote sensing techniques such as LiDAR and thermal imaging for comprehensive establishment of the extent of contamination. Biosensors, whether microbial, enzymatic, or cell-based, demonstrate high specificity and sensitivity for detecting pollutants. Advanced techniques such as next-generation sequencing, microbial source tracking, and environmental DNA analysis are instrumental in providing early warnings of contamination events. Additionally, future perspectives, as depicted in Figure 6, highlight further advancements in this field.

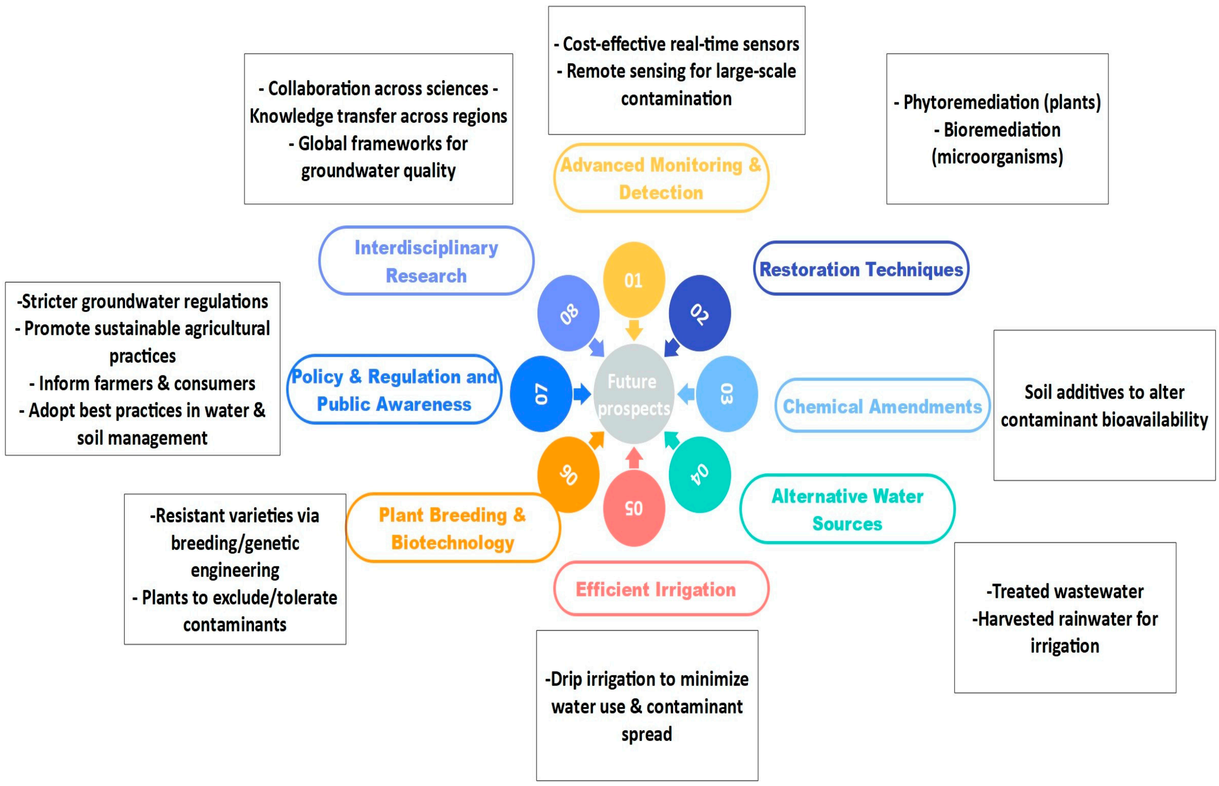

Figure 6. Future perspectives for the mitigation of geogenic contaminated water.

9. Conclusions

The formal analysis indicates that geogenic contaminants pose a significant threat to the long-term sustainability and productivity of irrigated fruit orchards. In fruit-growing regions of South Asia and globally, concentrations of arsenic (exceeding 0.3–0.5 ppm), fluoride (above 1.5 ppm), and boron (greater than 2.0 ppm) commonly surpass recommended safety thresholds. While fruit orchards may tolerate initial exposure due to their extensive root systems, prolonged accumulation of these toxic elements can lead to suppressed vegetative growth, impaired nutrient uptake, oxidative stress, and substantial declines in yield and fruit quality. The uptake and accumulation patterns of these contaminants are species-specific, with varying degrees of tolerance and sensitivity observed among crops such as citrus, grape, and guava, depending on the type and concentration of the contaminant.

Despite substantial research on contaminant toxicity in annual crops, studies focusing on perennial fruit trees remain limited. There is a critical need to (i) establish crop- and cultivar-specific tolerance thresholds for key geogenic elements and (ii) develop and promote effective mitigation strategies, including the use of soil amendments, salt- and contaminant-tolerant rootstocks, and alternative irrigation practices. Implementing such measures can significantly mitigate the harmful effects of contaminated groundwater, thereby enhancing the resilience and sustainability of fruit orchards and safeguarding agricultural productivity and human health.

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