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Review

Plant Tissues as Biomonitoring Tools for Environmental Contaminants

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Abstract: Environmental toxins pose significant threats to ecosystems and human health. Monitoring and assessing these toxins are crucial for effective environmental management and public health protection. Recently, plant species have garnered increasing attention as potential bioindicators for identifying and evaluating ecological toxins. Since plants often come into touch with harmful compounds in soil, water, and the atmosphere, they are particularly valuable for analyzing how human activities influence the terrestrial ecosystem, the aquatic system, and the atmosphere. This review paper emphasizes using plant species as a resource for tracking environmental pollution and analyzing contaminants. We focused on plants because they are significant indicators of soil, water, and air quality changes. Many plants have been used as bio-indicators to assess and predict pollution, toxicity, and environmental changes. These include *Allium cepa*, *Vicia faba*, *Pisum sativum*, *Zea mays*, *Nicotiana tabacum*, lichens, and mosses. The idea of bioindicators is discussed in the current paper, with a focus on plants as possible candidates for bioindicators for toxin assessment and related outcomes.

Keywords: bioindicator; environmental toxins; air pollutants; organic pollutants; plant response; biomonitoring

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1. Introduction

The proliferation of different environmental poisons has been aided by the development of industry and technology, creating distinct difficulties for public health. Multiple processes, such as industrial, agricultural, or natural ones, can produce environmental pollutants. These processes can have a serious negative impact on human health. Both natural and artificial environmental pollutants are ubiquitous in contemporary society. These pollutants include chemicals, radioactive hazards, soil, water, and air pollutants. They are categorized according to their composition and medium. Nine out of ten of us breathe air that contains pollutants beyond WHO guidelines, and the UN estimates that seven million people die from diseases and illnesses linked to air pollution. Climate change is partially caused by air pollution as well. Because of their persistence in the ecosystem and ability to permeate and accumulate through the food chain, toxicants are causing an increasing number of harmful health issues [1].

Toxins found in the environment may be chemical compounds. Pesticides, herbicides, volatile organic compounds (VOCs), and heavy metals are a few examples of chemical toxins. Pesticides can negatively affect health by contaminating drinking water. When pesticide use and health life expectancy longitudinal survey data were compared, it was discovered that for every 10% increase in pesticide use, the medical disability index for people over 65 increased by 1% [2]. The case of the Musi River in India demonstrates that compared to households with regular water, wastewater-irrigated villages have a higher incidence of morbidity. Natural causes are connected to water pollution. These pollutants can lead to both acute and chronic illnesses in humans, including heart failure, lung cancer, osteoporosis, and renal dysfunction. Heavy metals include arsenic, cadmium, lead, thallium, and mercury. Usually, ingestion, skin contact, or inhalation are how particles of these substances enter the body. For instance, consumed fish can become contaminated when heavy metals like mercury accumulate. Mercury exposure is possible for fish eaters. Between 2003 and 2009, research examined the health danger that heavy metals presented to people living in China's metropolitan regions [3]. Human health risk studies for heavy metals revealed that absorption was the primary form of exposure that negatively impacted human health. Overexposure to heavy metals in human internal tissues can have an impact on the central nervous system and serve as a pseudo-cofactor or promoter of several illnesses, including coma, headaches, and epilepsy. Both adults and children are thought to be at risk for health problems as a result of heavy metal exposure [4].

Moreover, toxins from the environment can also be biological. Bacteria, viruses, and parasites are examples of dangerous microorganisms that are considered biological pollutants. These germs can spread bacterial infections, such as salmonella, *E. coli*, the Zika virus, and malaria parasites, to people through the air, water, and food [5]. Radioactive contamination is another type of environmental toxin that can be harmful to human health. Radiation exposure can result from certain medical procedures and nuclear power plants. Low-level radiation's effects on health are unknown [6]. Toxins have a range of impacts on the environment and organisms: they can kill animals and destroy significant ecosystem components or have little effect on some abiotic factors or resistant organisms. Toxins have various effects on plants and humans, as depicted in Figure 1. The kind and composition of the toxic material, the organism's age, size, and species, the temperature, and the physical and chemical properties of the surrounding environment (aquatic or terrestrial) all affect how much damage is done [7].

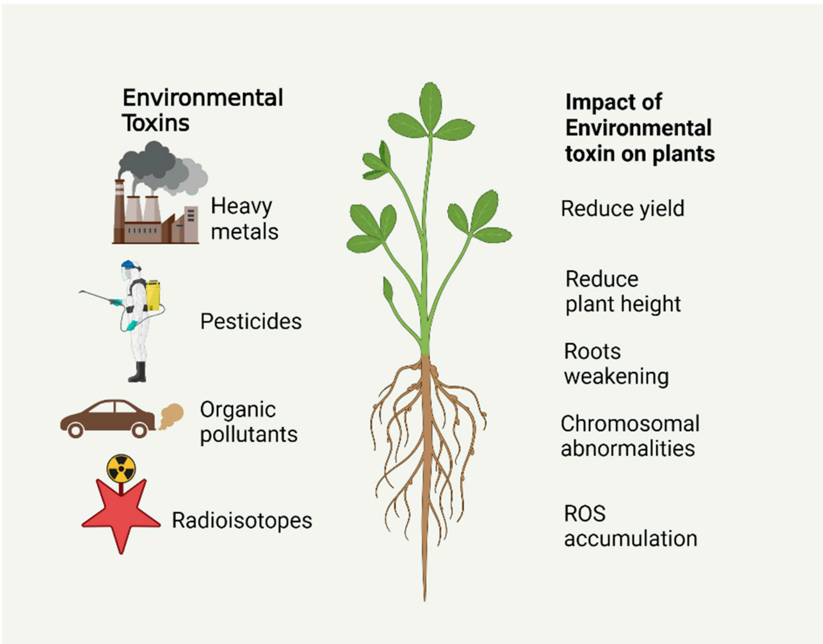

Figure 1. Various environmental toxins and the impact of the toxins on plants.

An essential component of environmental toxicology is figuring out how to keep an eye on the chemicals present in the environment. The detection of sensitive biochemical markers, such as proteins, whose levels alter in the presence of a specific toxin, or alterations in a single "indicator" species, whose health and well-being serve as indicators of environmental conditions and other species' health, are the usual bases for monitoring [8]. Plants have been used for a long time as bioindicators of toxins found in the environment. They have spent decades participating in the ecological risk assessment of radioactively and chemically polluted soil and water, solid wastes, industrial and agricultural pollutants, and food additives. Plants can uniquely accumulate and concentrate toxins from their surroundings. Plants can gradually accumulate toxins in their tissues through processes like soil uptake, water absorption, and atmosphere adsorption [9].

Additionally, these toxins can biomagnify within the food chain, making plants useful markers of the degree of environmental contamination. Unlike conventional ecological monitoring techniques, which frequently call for destructive soil, water, or air sampling, plant tissue sampling is non-destructive. It makes sample collection a less intrusive and more environmentally friendly monitoring method because it allows samples to be obtained without substantially changing or harming the environment [10]. Plants are commonplace in terrestrial and aquatic ecosystems, including wetlands, urban areas, and forests. Due to their widespread distribution, they are easily sampled in various settings, allowing for thorough local and global environmental toxin monitoring. Plant tissues can integrate ecological contamination both spatially and temporally. By examining toxin levels in diverse plant tissues such as leaves, roots, and stems, as well as across different plant species, scientists can learn about the spatial patterns of contamination in a particular area [11]. Furthermore, tracking the accumulation of toxins over time in annual or perennial plant species can yield important insights into temporal patterns and shifts in the levels of environmental pollution. All these factors make plants an excellent choice for being used as biomonitoring tools [12].

2. Types of Environmental Toxins

In the modern era, the conversation about environmental pollutants is gaining special interest as people realize the consequences of their industrial activities. Environmental toxins, encompassing diverse chemical agents, pollutants, and contaminants, affect human health and ecological systems. Environmental toxins have a variety of complex mechanisms that contribute to their diverse toxicological profiles and subsequent deleterious effects [13]. The main ways that heavy metals cause harm to cells and systemic dysfunction are by oxidative stress and by interfering with enzymatic functions. On the other hand, organic pollutants like pesticides cause neurological disorders and cognitive impairments by interfering with neurotransmitter signaling pathways and exerting neurotoxic effects. Additionally, some toxins cause endocrine disruption, which throws off hormonal balance and causes developmental and reproductive abnormalities [14].

2.1. Heavy Metals as Environmental Toxins

While naturally occurring in the environment and necessary for existence, heavy metal (HM) accumulation in living things can be hazardous. The nucleus, mitochondria, endoplasmic reticulum, cell membrane, and specific enzymes involved in damage repair, detoxification, and metabolism are among the cellular organelles and biological system components that have been demonstrated to be impacted by heavy metals (Figure 2). The heavy metals that most frequently contaminate the environment are lead, copper, nickel, chromium, cadmium, arsenic, and mercury. [15]. For instance, humans and animals can be exposed to cadmium in various ways, which can be released into the atmosphere through artificial and natural means. Both surface runoff and industrial waste absorb cadmium, contaminating the aquatic environment's soil and sediments. A person may become poisoned with cadmium through food consumption, air pollution, or water consumption. Nothing about cadmium benefits plant growth and metabolic processes [16]. Another heavy metal, mercury, may be found in the biosphere. HMs are becoming more prevalent in the atmosphere because of human activity.

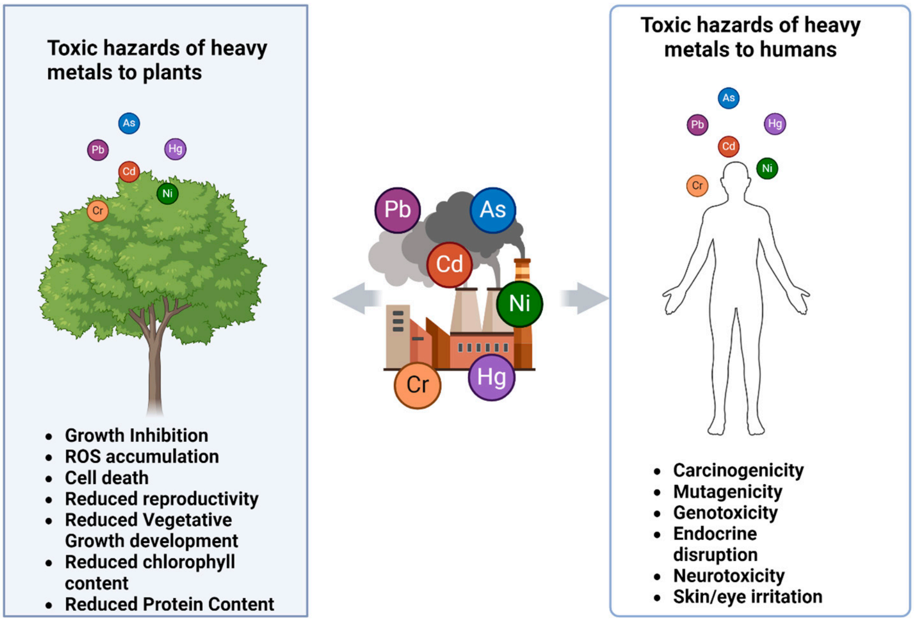

Figure 2. Impact of heavy metal on plants and humans. Heavy metals pose various hazards to plants and humans.

Mercury changes into methylmercury, which is extremely toxic when it comes into contact with aquatic sediments [17]. The research found that hazardous germs that have infected shellfish, fish, and animals can enter the human food chain and infect humans. After the body absorbs it, it enters circulation and produces a variety of neurological issues [18]. Lead is another metal that is not biodegradable and may be found in nature at minute levels. Because of mining, the combustion of fossil fuels, and other human activities, lead levels in the atmosphere are constantly rising. When lead exposure exceeds suggested limits, it harms human health [19]. A study found that children are more vulnerable to lead poisoning and that exposure to dust contaminated with environmental lead increases the severity of the poisoning [20]. Some heavy metals, such as chromium, are found to be carcinogenic. In the environment, chromium (III) and chromium (IV) are its two stable oxidation states (VI). Iron (III) is a less hazardous iron (VI) form. They are capable of interconverting to one another during industrial processes. However, because chromium (III) is less toxic than chromium (VI), its conversion is less detrimental to the environment. Numerous industries that use chromium endanger local climates.

The ferrochrome industry emits the most chromium compared to natural environmental emissions [21]. One of the other heavy metals, nickel, when inhaled, may cause numerous negative effects on humans, including allergies, lung and nasal cancer, kidney and cardiovascular diseases [22]. A heavy metal that is typically found in nature is zinc. Zinc is necessary for plants and animals, but it can poison the surrounding ecosystem when it is in excess. Zinc is mostly obtained by mining and smelting; the process of processing minerals releases a large amount of zinc into the atmosphere, which affects ecosystems and living organisms. The mode and extent of exposure determine the toxicity of zinc [23]. Some heavy metals are present in trace amounts, but their presence at nanogram levels can cause toxicity, such as antimony. Those who work in industrial areas may inhale antimony and become toxic. Physiological abnormalities include pancreatitis, cardiotoxicity, and respiratory issues (pleural adhesions, chronic emphysema, chronic bronchitis, respiratory irritation, and dormant TB) that can result from antimony poisoning. It is carcinogenic and affects reproduction as well [24].

2.2. Organic Pollutants as Environmental Toxins

Some environmental toxins are present in the form of organic pollutants. Persistent organic pollutants (POPs) are hazardous organic compounds primarily from human activity and have garnered attention in recent decades [25,26]. POPs are a persistent, bioaccumulative, and long-range transportable class of organic chemicals based on carbon. POPs in the environment come in three different varieties: chemicals used in industry and technology, such as polychlorinated dibenzofurans (PCDFs), polychlorinated biphenyls (PCBs), and perfluorooctanesulfonate (PFOS); (3) pesticides, especially organochlorine pesticides (OCPs) like dichlorodiphenyltrichloroethane (DDT) and its metabolites; and (4) byproducts of industrial processes, like polychlorinated dibenzo-p-dioxins (PCDDs), polychlorinated dibenzofurans (PCDFs), and polyaromatic hydrocarbons (PAHs) [27]. Since PAHs can be effectively metabolized and thereby inhibit further bioaccumulation, they do not strictly fall under the POP category and are only designated as such under the Aarhus Protocol [28,29]. However, many studies often categorize PAHs as POPs because of their lipophilicity and continuous release [30].

According to another study, POPs can be divided into four categories: intentionally produced substances, chemicals currently being investigated, and those that have their production and usage restricted or eliminated. POPs can be classified as chemically brominated, chlorinated, or fluorinated compounds. POPs are remarkably resistant to environmental degradation; they can endure in soils, aquatic environments, food chains, and, eventually, human bodies, even after production has stopped. Due to their lipophilic properties, these pollutants can accumulate in various environmental elements, in the tissues of organisms, and over long distances through the atmosphere [31]. The characteristics mentioned above facilitate their biomagnification and bioaccumulation in animals, presenting noteworthy risks to human well-being and the integrity of natural ecosystems.

These contaminants threaten long-term human and wildlife survival by disrupting the food chain. Worldwide populations, including humans and animals, may be exposed to POPs for an extended period. As these pollutants move up the food chain, they can build up in the fatty tissues of living things. This causes their concentration to rise. There is scientific proof that POPs are harmful to human health. Exposure to these toxins can lead to a host of health issues, including disrupted hormones, heart disease, cancer, diabetes, birth deformities, and impaired immunological and reproductive system performance [32].

2.3. Radionuclides

Radionuclides are unstable isotopes of certain chemical elements. This instability—which results in the emission of particles with various energies—is often caused by excess energy in the atomic nucleus. Natural radionuclides release three types of radiation: alpha (α), gamma (γ), and beta (β-). A-particles cause 20 times more biological damage than an equivalent dosage of β- or γ radiation. They have the most potent biological impacts of all these kinds [33].

In contrast to α- and β-particles, which usually do not penetrate deeply into living or non-living materials, γ-radiation does, especially at the higher energy spectrum. This suggests that when examining the biological and ecological implications of radionuclide pollution, α- and β-emitters are only significant if they are components of living organisms. Conversely, as internal and external components, γ-emitters contribute significantly to the total absorbed dosage [34].

For the health of ecosystems and human welfare, elevated quantities of radioactive elements in the environment from geological or industrial operations might be exceedingly harmful, particularly if they accumulate in the food chain [35]. Numerous earth surface processes can cause these radioactive elements, which include uranium (U), cesium (Cs), strontium (Sr), radium (Ra), and radon (Rn), to enter the soil, surface waters, and ground waters. According to research, radioactive materials from nuclear and civil industrial processes leak into the natural ecosystem and pose a health risk to people. Moreover, radionuclides are a naturally existing component of the surroundings. They are very susceptible to radioactive decay, which can produce a variety of ionizing radiations, including gamma rays or fast alpha or beta particles [36]. These ionizing radiations can disturb the functioning of significant macromolecules such as deoxyribonucleic acid (DNA) by displacing electrons and generating ions. Gupta, et al. [37] claim that life has only evolved to resist trace levels of radionuclides in soils. They can penetrate the food chain because they are resilient and long-lasting in soil and water. The transmission and subsequent buildup of radionuclides have received increased attention due to the soil–plant continuum [38].

Plants absorb radionuclides from the soil, which build up in higher creatures farther up the food chain and cause chronic internal radiation exposure and ion toxicity. Exposure of plants to radionuclides, specifically U, causes various toxic effects that vary in severity and are dose-dependent. These effects include lesions on leaves, growth inhibition, and even death. For instance, Pinus densiflora younger trees and Zea mays plants exhibit delayed growth. According to reports, radionuclides like "Th" are highly toxic and non-essential. They also show obvious toxicity when accumulated excessively. They have been shown to alter cell membrane shape and obstruct vital plant processes, even at extremely low doses. Furthermore, scattered radionuclides from nuclear accidents like Fukushima have contaminated coastal ecosystems [39].

Various studies have been conducted worldwide to analyze the impact of radionuclides on crops. One study found that potato lateral roots and epidermis have high (U) accumulation that exceeds the threshold limit and may harm human health. According to Soran, et al. [40], Th and U's transfer coefficients from the soil–rice system, in contrast, range between 0.01–1.20 and 0.03–0.67, respectively. Similarly, edible parts of Eruca sativa, Mangifera indica, Psidium guajava, and Lycopersicon esculentum show potential for accumulating Th and U. Th has been found in a number of plant species, including wheat, ferns, medicinal mushrooms, and ferns, according to Fu, et al. [41]. Plants' antioxidative defense systems are activated and reactive oxygen species (ROSs) are formed more quickly when adversity stress mediated by U is present. Plants that accumulate uranium experience toxic biochemical, physiological, and genetic effects. Reduced plant growth, inhibition of photosynthetic activity, oxidation of lipid membranes, elevation of reactive oxygen species (ROS) generation, modification of enzyme activities, oxidation of proteins, and breakage of DNA chains are some of these impacts.

3. Mechanism of Plant Toxin Uptake

Numerous researchers have investigated the mechanisms underlying plants' uptake of contaminants. According to Baker [42], plants have two functions, "accumulators" and "excluders." Contaminants are concentrated in the aerial tissues of accumulators. They biodegrade or biotransform the contaminants into inert forms inside their bodies. The excluders restrict the amount of pollutants that can enter their biomass [43]. In order to absorb essential micronutrients from their environment, even in low parts per million concentrations, plants have evolved specialized and efficient processes. Figure 3 illustrates how plant toxins can be absorbed through the foliar or root absorption routes.

Plant-produced chelating agents, pH changes, and redox reactions enable roots to solubilize and absorb micronutrients from very low quantities in the soil, even from nearly insoluble precipitates. Many tiny, non-polar toxins can passively diffuse across the root membrane during the passive uptake mechanism, which allows for root uptake. Concentration gradients help with this, as toxins migrate from higher-concentration areas (soil) to lower-concentration areas (root). Lettuce (*lettuce sativa*) uses this mechanism to transfer contaminants from soil to roots. An additional mechanism is an active uptake, whereby plants utilize active transport systems to absorb particular toxins in opposition to concentration gradients [44]. Transporter proteins that are enmeshed in the root cell membranes are used in this process. These transporters have two possible energy sources: primary active transport, which uses ATP, and secondary active transport, which uses pre-existing ion gradients. *Arabidopsis thaliana*, a model plant, is the best example of this uptake mechanism [45]. It usually takes toxins via specific transporter proteins embedded in the root cell membrane. A process known as endocytosis allows some toxins to enter root cells by engulfing the toxin molecules in the cell membrane and forming vesicles that carry them inside the cell. For example, wheat (*Triticum aestivum*) usually takes silver nanoparticles from contaminated soil through endocytosis [46].

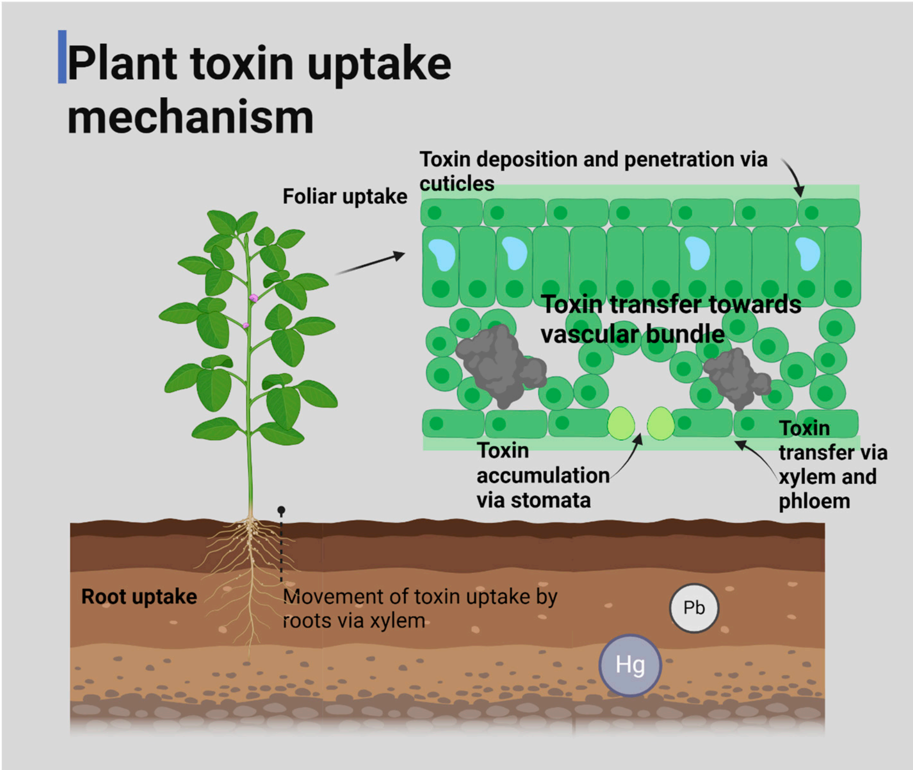

Figure 3. Plant toxin uptake mechanism. Plant toxin uptake can take place through foliar or root uptake. Through foliar uptake, toxins transfer through cuticles and vascular bundle. Through root uptake, toxins transfer takes place via xylem.

Plants can also uptake toxins through the foliar pathway by cuticle or stomatal uptake, as shown in Figure 3. In cuticular uptake, toxins soluble in water cannot pass through the cuticle, the outermost layer of leaves, which acts as a hydrophobic barrier. However, lipid-soluble poisons can permeate the cuticle and reach the leaf tissue. Meanwhile, through stomatal uptake, stomata control the exchange of gases. These holes can receive toxins from gases or tiny droplets inside the leaf. They may either be absorbed straight into the cells or diffuse through the spaces between them once inside [47]. Trichomes, which resemble hairs, are found on the leaves' surface and absorbed by them. Certain toxins can stick to trichomes and change chemically there or get swept into the leaf tissue by precipitation or dew.

Furthermore, plants have created extraordinarily complex systems for transporting and storing micronutrients. Toxic materials are absorbed, translocated, and stored by processes that are comparable to those responsible for key components of their chemical composition. Consequently, micronutrient absorption pathways are very important in phytoremediation. Ion uptake and translocation are facilitated by a number of recognized transport mechanisms or specialized proteins embedded in the plasma membrane of plant cells. These mechanisms include co- and anti-transporters, which use the electrochemical gradients generated by ATPases to drive the active uptake of ions, channels, which allow ions to be transported into the cell, and proton pumps, which are ATPases that consume energy and produce electrochemical gradients. Different ions are taken up by each transport mechanism [48]. A key problem is the interaction of ionic species during the absorption of various heavy metal pollutants. Since extracting root biomass is usually impracticable, translocation into shoots after root absorption is preferable.

Plant uptake–translocation mechanisms are likely tightly controlled. Trace elements are typically accumulated by plants only during fulfillment of their immediate metabolic needs. These minimal requirements—between 10 and 15 ppm of most trace elements—suffice for most needs. “Hyperaccumulator” plants are an exception, as they can absorb harmful metal ions at thousands of parts per million. Other concerns are the mechanisms by which plants, particularly hyperaccumulating ones, store toxic metal ions and guard against metal toxicity. Several mechanisms are involved. Evidently, one important one is Hoover storage. A pump pulls nutrients and other materials from the soil into the roots of plants through the evaporation of water from plant leaves. It is also through this process, known as evapotranspiration, that contamination is transferred into the plant shoots. Contamination is eliminated while preserving the original soil because it is transferred from the roots to the harvested shoots [49].

3.1. Bioaccumulation

The term “bioaccumulation” describes the buildup of materials—usually toxins or pollutants—in living things at a rate faster than their removal. Numerous interacting factors are involved in this process, which happens in various environmental compartments, including aquatic and terrestrial ecosystems. Although bioaccumulation can occur naturally to some extent, human activity has made it more common and contaminated the environment extensively [50]. Because toxins are biomagnified through the food chain, the effects of bioaccumulation go beyond ecological disruptions to potentially harmful effects on human health. The ability of toxins to bioaccumulate within organisms is influenced by various factors. The absorption, distribution, and retention of toxins are significantly influenced by their physicochemical characteristics, including lipophilicity, water solubility, and chemical stability. Factors about the organism, such as feeding habits, metabolic rate, and physiological adjustments, impact how effectively toxins accumulate. Environmental factors that affect an organism’s metabolism and toxin bioavailability include temperature, pH, and dissolved oxygen levels.

Furthermore, the movement of toxins within ecological systems is greatly influenced by food web dynamics and trophic interactions. “Bioaccumulation mechanisms” refers to various methods by which organisms take up, hold onto, and absorb toxins from their surroundings. These mechanisms involve absorption into tissues or storage organs like the liver and fat deposits, followed by uptake through ingestion, dermal contact, or respiratory exposure. Once ingested, toxins may either remain in their original form or undergo biotransformation, converting them into less toxic or more polar compounds. Environmental factors, organismal features, trophic relationships within food webs, and the physicochemical properties of toxins are some factors that affect bioaccumulation dynamics [51].

Heavy metal bioaccumulation is a process that occurs when dangerous metals or chemical compounds form bonds inside a cell. Metal bioaccumulation is impacted by various exposure pathways (diet and solution) and geochemical effects on bioavailability. The bioaccumulation of metals is particularly useful as an indicator of exposure because metals are not metabolized. Certain plant species are capable of concentrating heavy metals such as Cd, Zn, Co, Mn, Ni, and Pb up to 100 or 1000 times greater than non-accumulative (excluder) plants [52]. The majority of the time, bacteria and fungus in the rhizosphere around plants can aid in the mobilization of metal ions and increase the proportion that is bioavailable. Compared to inorganic compounds, their contribution to the removal of organic contaminants is even greater [53]. However, bioaccumulation is a useful integrative indicator of the exposure of organisms to chemicals in contaminated environments. Bioaccumulation requires biomass to have some level of bioactivity. For pollutants to be absorbed by cells through metabolic processes, they must be alive. The entire cell absorbs metal ions during the process of bioaccumulation. Metals enter living things’ cells through the same channels that allow nutrients to do so. They absorb metals and vital nutrients like calcium and magnesium that unicellular organisms require to survive.

3.2. Biomagnification

When an organism's diet serves as its main exposure route, a condition known as biomagnification occurs when the concentration of the pollutant in the organism is higher than the concentration of its food. The steady rise in pollutant concentrations with rising animal trophic status is known as food web biomagnification. It clarifies how contaminants build up trophically within food webs [54]. A food chain is composed of three groups: consumers, plants, animals that devour plants, and top predators, or creatures that consume other animals [55]. In the food chain, pollutants and toxins can enter at any time, but because top predators consume larger meals and accumulate more toxins over time, these substances tend to accumulate in their bodies. The environment is significantly impacted by biomagnification.

For instance, the decrease in bird populations has been connected to pesticides like dichloro-diphenyl-trichloroethane (DDT). Insects exposed to DDT during its widespread use in the 1950s and 60s would subsequently absorb it into their diets. After consuming the insects, the birds absorb the DDT into their bodies. Consequently, over time, the birds' bodies would contain higher concentrations of DDT. Because the eggs the birds laid had delicate shells that cracked before the eggs could hatch, bird numbers decreased. Certain pesticides, herbicides, and other chemicals, as well as heavy metals like lead and mercury, are examples of substances that can experience biomagnification. Ecosystems are frequently exposed to these substances due to industrial processes, mining, and agriculture. One of the most well-known instances of biomagnification is the insecticide DDT, which was widely employed to control insects in agricultural and other settings in the middle of the 20th century. In addition to being extremely toxic to various insect species, DDT also remains in the environment for extended periods [56].

Significant effects of biomagnification are also seen in human health. For instance, there is evidence connecting the pesticide DDT to developmental disorders, cancer, and reproductive issues. Mercury can cause neurological issues such as memory loss and tremors. It can be especially harmful to young children and expecting moms. One of the best-known examples of biomagnification is the tale of the insecticide DDT. To control insect populations, DDT was widely employed in the middle of the 20th century. Subsequent research, however, revealed that DDT was extremely hazardous to a wide variety of creatures, including raptors. Following its discharge into the environment, DDT was concentrated in the fatty tissues of tiny creatures such as plankton and small fish [57]. These smaller organisms were eaten by larger predators, such as preying birds, which increased the concentration of DDT to the point where it seriously harmed the birds' reproductive systems.

Fish mercury exposure is another instance of biomagnification. Mercury is an element that occurs naturally and is discharged into the environment by several human activities, such as mining and burning coal. Fish fatty tissues can hold onto mercury when introduced into an aquatic environment. Mercury levels are amplified to the point where human consumption of fish may be hazardous when larger fish eat smaller fish. Numerous detrimental effects on the environment and the living things that inhabit it can result from biomagnification [58]. As with the bald eagle, it may result in population declines in specific species. When animals or humans eat contaminated organisms, it can also result in health issues. Additionally, the economy may be impacted by biomagnification as it may lead to a fall in fish populations, which many rely on for food and money.

3.3. Biomonitoring

Biomonitoring refers to using living organisms as monitors to assess environmental toxins in the ecosystem. Two main methods for living organisms to monitor environmental toxins are biomonitoring and biosensing. The integrated or passive approach, also known as in situ biomonitoring, is predicated on observing organisms naturally occurring in the environment under study. It considers ecological and climatic factors and is primarily used to monitor long-term effects. Active biomonitoring involves introducing organisms into the study site grown in controlled environments (like a greenhouse) or removed from a control site (like transplanting lichens that cannot be grown) [59]. Using a laboratory setting with strict controls is also feasible to develop plants and expose them to contaminants. This method is primarily employed to track immediate effects under particular exposure circumstances. The biological nature of the bioindicator is the primary constraint on biomonitoring; success hinges on the organism under study being present at a sufficiently high level, its sensitivity to biotic or abiotic stimuli, or even its competition with other organisms or species [60]. Therefore, the impact of ecological factors may be sufficient to produce an inaccurate assessment of the effects of the pollutants under study.

4. Plants as Bioindicator of Environmental Toxins

An indicator plant is a kind of plant that displays symptoms in response to phytotoxic amounts of a pollutant or combination of pollutants. Since plants actively participate in the cycling of nutrients and gases like carbon dioxide and oxygen, they are essential to the monitoring and maintenance of the ecological balance [61]. Additionally, they offer a huge leaf surface where air pollutants can be absorbed and gathered. For a long time, green plants have been used as air pollution markers. It is commonly known that vegetation canopies can serve as sinks for air pollutants, including gaseous and particulate. Plants vary in their susceptibility to air pollution and how they respond to it. While tolerant plants can be employed to green urban areas and improve air quality, more sensitive plant species act as biological monitors of air pollution [62]. Understanding how plants respond to air pollution at the physiological and biochemical levels requires looking at the factors that affect resistance and susceptibility [63]. In the Iranian city of Isfahan, the effects of air pollution on Acacia (*Robinia psudo-acacia*) leaves were investigated. Plants that are exposed to unfavourable environmental conditions, such as higher concentrations of heavy metals, may produce more reactive oxygen species (ROS), which include hydroxyl radical (OH), superoxide hydrogen peroxide (H_2O_2), and singlet oxygen [O_2] [64]. ROS oxidize unsaturated fatty acids or other lipids, modifying proteins, damaging DNA, and producing MDA as a byproduct. Considering the vital function that ROS detoxification plays in plants' defense mechanisms against cellular damage, it would seem reasonable that plants that accumulate metals would have highly potent defense mechanisms against oxidative stress and detoxication, enabling them to thrive in contaminated environments [65].

Regulations, effective regulation, and the identification of locations with greater concentrations of heavy metals are required. Mandatory monitoring of these metals should also be put in place due to their toxicity and propensity for bioaccumulation. It is common knowledge that certain plants can absorb trace elements from their surroundings. Thus, they have been employed in several monitoring studies, offering low-cost data on environmental quality and the benefit of simple sampling. In several studies, herbaceous plants—which are more common in urban areas—such as *Taraxacum officinale*, *Carduus nutans*, *Plantago major*, and *Urtica dioica* were used as bioindicators [65–68]. Moss has also been shown to be a useful bioindicator of environmental toxins, and it is a more reliable indicator of air pollution caused by heavy metals in urban areas than the leaves of vascular plants. Because of this, bryophytes are thought to be the best biomonitoring agent for environmental pollution. Moss bag techniques are currently used to provide a dense, flexible, and inexpensive monitoring design that can display both vertical and horizontal gradients and spatial and temporal trends for various inorganic and organic pollutants. These techniques have been successfully applied to the biomonitoring of elements that may be dangerous, including rare earth elements and persistent organic compounds, mostly polycyclic aromatic hydrocarbons [69]. According to earlier research, certain species can bioaccumulate heavy metals. They have yet to, however, be investigated concurrently, in identical contaminated environments, or with the physiological response in mind. Managing the pollution of harmful elements in conjunction with the use of commonly accessible weeds such as *Plantago lanceolata* L., *Amaranthus retroflexus* L., *Trifolium pratense* L., *Rumex acetosa*, and ancient ornamental plant (*Alcea rosea*), which is also known for its capacity to accumulate trace metals, appears to be a crucial procedure that enables comprehensive assessment of trace metals environment contamination (Table 1) [70].

Table 1. Some environmental toxins and bioindicator species for the toxins.

Sr.#	**Environmental Toxin**	**Bioindicator Species**
1.	Ozone (O_3)	Tobacco (*N. Benthamiana*)
2.	Particulates and heavy metals	Moss and lichen
3.	Sulphur dioxide (SO_2)	Mango, alfalfa, soybean, cucumber, pepper
4.	Nitrous Oxide (NO_2)	Tomato, lettuce, corn, wheat
5.	Acetylene	Orchid and cucumber
6.	PAN	Tobacco, moss, and bean
7.	Pesticides	Lichen, cabbage, ray-grass
8.	Volatile Organic Components (VOCs)	Cabbage
9.	Nitrogen	Moss, ray-grass, lichen
10.	Chloride and Floride	Ray-grass, lichen, cabbage

Many biological plant symptoms have been linked to pollution in recent times. These include changes in pH that are observed after growing specific acidophytes, such as hair grass (*Deschampsia flexuose*), sunflower (*Drosera rotundifolia*), or common ling (*Calluna vulgaris*); changes in nitrate content in ecosystems linked to growing wild barley (*Hordeum murinum*), French mercury (*Mercurialis annua*), or large nettle (*Urtica dioica*); and changes in total soluble salt content that occur after the growth of certain lower-pH plants may be a useful indicator of the effectiveness of a metal plant extraction process [71].

There are environmental pollutants in both urban and rural locations. Numerous investigations have been carried out to evaluate their impact. *Tillandsia purpurea* and *Tillandsia latifolia* species were assessed as biomonitors in urban and industrial settings in recent research [72]. To determine metal buildup, plants were removed from a non-contaminated region, moved, and left for three months in research sites. Al, As, Ba, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Ni, Pb, Rb, Sb, V, and Zn were among the sixteen elements that were measured by ICP-MS analysis. The datasets were assessed using one-way ANOVA, exposed-to-baseline (EB) ratio, and principal component analysis. There were none between the species, although most of the factors showed notable variations between the research regions. As, Cd, Cr, Cu, Fe, Ni, Pb, Sb, V, and Zn showed EB ratios > 1.75 for both *Tillandsia* species in the proximity of the industrial region, demonstrating the impact of the Smelter facility. The fact that both plants' EB ratios for Ba, Sb, and Zn in the urban area were higher than 1.75 indicates that pollutants may be escaping from moving cars. The majority of the components, according to PCA, originate from dust resuspension, industrial activities, and vehicle sources.

An alternative investigation assessed the phytoremediation capacity of six tree species in the Faisalabad industrial and residential areas (*Azadirachta indica*, *Cassia fistula*, *Conocarpus erectus*, *Eucalyptus camaldulensis*, *Morus alba*, and *Populus deltoids*, respectively) based on the levels of lead (Pb), zinc (Zn), cadmium (Cd), and copper (Cu) in the leaves and barks of these plants. Zn > Pb > Cu > Cd was the sequence in which the seasonal concentrations of heavy metals in the leaves and bark of these trees dropped at both research locations. When comparing the heavy metal contents of trees grown in residential and industrial areas, it was found that the leaves and barks of the former had higher concentrations of heavy metals during the summer than during the winter. Different tree species were shown to have varying capacities for accumulating heavy metals. For example, trees in the following order were found to have lower levels of Cd accumulation: *A. indica* > *P. deltoids* > *C. fistula* > *E. camaldulensis* > *M. alba* > *C. erectus*. The order was different for the other heavy metals. All things considered, the intended heavy metals were successfully taken from the surrounding air by *M. alba*, *E. camaldulensis*, and *A. indica*. Because they may remove heavy metals through phytoremediation, three of the six tree species that are commonly planted in Faisalabad City—*M. alba*, *E. camaldulensis*, and *A. indica*—are advised for usage in both residential and commercial contexts [73].

The most widely used assays to investigate the mutagenicity of different pollutants in plants are those that rely on finding chromosomal abnormalities in plants such as *Zea mays*, *Vicia faba Tradescantia*, and *Allium cepa* [74–77]. One test that may be used to quickly screen for the negative effects of chemicals is the *Allium cepa* chromosomal aberration test. Because of its sensitivity, the *Allium cepa* test was the first of nine plant assay systems assessed by the US Environmental Protection Agency's Gene-Tox Programme [78,79]. The computation of the different chromosomal aberration fractions and the proportion of aberrant mitotic events forms the basis of the experiment [80]. *Tradescantia* is another essential plant for mutagenesis research. Assays for chromosomal aberration, stamen–hair mutation, and micronuclei production may be performed on this plant [81]. It has been used to assess the air quality in high-traffic areas, landfill vent pipe air quality, and urban waste storage facilities [82,83].

Tradescantia has also been used to analyze soil and water contamination and evaluate the effectiveness of bioremediation at hazardous waste sites [84–86]. *Vicia faba* is another plant that is commonly used as a biosensor. For a number of compounds, the sister chromatide exchange test based on *Vicia faba* has produced favorable findings [87]. Tobacco plants heterozygous for the sulphur (Su) nuclear gene have also shown promise as useful biomonitoring plants, although being less frequent. In *Nicotiana tabacum*, Su is a nuclear-encoded semi-dominant aurea mutation. Homozygous plants (Su/Su) exhibit a pale yellow color and lack photosynthetic ability, while heterozygous plants (Su/+) have photosynthetic competence and display a yellow-green phenotype that is distinct from the green wild-type plants (+/+) [88,89]. When compared to plants that were not treated, Su/+ plants subjected to gamma radiation and chemically treated exhibited a substantial increase in the quantity of dark-green spots on light-green leaves. Some studies have used higher plants as bioindicators and biomonitoring tools. Higher plants are subject to numerous categories of ecosystem pollutants because of their immobility and prolonged life, making them appear as valuable biological indicators [90]. Pollutants often have an overall negative impact on plant growth, performance, and population intensity. It can include changes in morphology as well as metabolic and cellular changes. Generally speaking, the first biological indicator is thought to be external vegetative symptoms. However, in most cases, additional botanical and chemical analyses would be required to validate such assumptions. Certain higher plants could monitor the majority of PTEs [91].

5. Plants as Cues to Environmental Conditions

Plants are sessile and, therefore, cannot avoid biotic and abiotic environmental cues. Plants have evolved various adaptations and mechanisms to deal with biotic and abiotic threats to their survival. When certain biological systems sense a stressor in the environment, they activate. The physiological reactions and responses required to deal with the stressor are subsequently triggered by this activation. Through various signalling pathways, cells transform external stimuli into modifications in gene expression. These channels carry signals from cytoplasmic or cell surface sensors to the parts of the cell in the nucleus that regulate transcription [92].

The cell can communicate information about its internal and external states to the nucleus through these signalling pathways, and the nucleus can then change the expression of certain genes in response. The plant gains greater stress tolerance through modifications in gene expression. Stressful situations are sensed and responded to by cells through cellular signalling pathways. These pathways identify signals of stress or damage from the cellular environment and subsequently initiate the proper physiological and biochemical reaction to that stress [93].

A thorough investigation of environmental pollution must consider the potential physical, chemical, and biological effects and our understanding of ecological systems and chemical compounds. A comprehensive pollution examination should evaluate possible environmental impacts, integrating the most recent knowledge of environmental mechanisms and chemical constituents [94]. In situ biomonitoring involves the observation of bioindicators, bio-monitors, and species of organisms with limited ecological tolerance for xenobiotics [95].

Alterations in bioindicator behavior, function, or population may be signs of environmental degradation. Advanced biomonitoring methods can offer a more profound understanding. The biological features of an environment can be closely monitored and assessed using the right sensors and measurement tools, along with various techniques and protocols. Bioanalytical methods like biosensors and bioassays can gather and examine environmental samples outside the body. These tools enable the samples to be examined for relevant biological markers. Bioanalysis is an area of environmental sciences that is rapidly expanding. It has developed and is shown to be successful in monitoring and assessing ecological quality since the early 20th century. These days, various bioanalytical methods are used for this, including bioassays.

5.1. Factors Influencing Plant Selection as Toxin Monitors

Plants play a crucial role in detecting environmental stressors by exhibiting observable changes in their surrounding environment, making them bioindicators for monitoring pollutants [96]. These alterations may manifest as lesions, color shifts, changes in leaf morphology, or modifications to growth patterns. Environmental contamination can be detected early through the use of indicator species, which can be easily identified, collected, and monitored over time [97].

Fast growth rate, high reproductive potential, and accessibility are some traits that make using particular plant species for monitoring feasible. The monitoring site's environmental conditions must allow plants to endure and flourish. Plant growth and health are influenced by various factors, including temperature, soil pH, moisture content, and sunlight exposure. Reliable monitoring results are ensured by choosing species suited to the local environment [98]. Non-destructive sampling techniques are preferred to reduce ecological disturbance and make longitudinal research possible. Plants that yield samples (leaves stems, or roots) that can be collected without seriously damaging the plant or its population are desirable. The following elements should be considered when choosing a bioindicator:

- Describing responses that are concerning for the ecosystem that can be readily measured;
- Possessing a unique reaction that can forecast the species' or ecosystem's reaction to the stress;
- Calculating the answer with a reasonable level of precision and accuracy;
- Being predicated on an understanding of the pollutant and its properties.

The ability of plants to absorb toxins from their surroundings varies from species to species. Certain species can absorb and store pollutants in their bodies, while some could be more efficient. The sensitivity of monitoring is increased by choosing plants with a strong affinity for particular toxins. For example, alpine prickly ash *Thlaspi caerulescens* is well known for its capacity to hyperaccumulate nickel, cadmium, and zinc. The plant's potential for phytoremediation of heavy metal-contaminated soils has been thoroughly investigated. So, the plant can be used as an excellent biomonitor of heavy metals [98]. Another hyperaccumulator species is *Arabidopsis helleri,* which is especially concerned with zinc and cadmium [99]. Its physiological and genetic characteristics make it a good model organism for studying mechanisms of metal hyperaccumulation.

5.2. Plants as Indicator of Air Pollution

Certain plants, like lichen species (*Parmelia* spp.), symbiotic organisms of fungi and algae or cyanobacteria, are excellent air pollution markers. Because some lichen species are susceptible to air pollutants like nitrogen oxides and sulphur dioxide, they can be used as helpful markers of air quality in urban and industrial areas [100]. *Tilia* spp. is another excellent marker of air pollution [101]. Because linden trees are susceptible to ozone pollution, high ozone levels can cause them to exhibit visible symptoms like bronzed or stippled leaves. *Taraxacum officinale* was used as a sentinel organism in a study to characterize the impacts of airborne nanostructured pollutants. *Taraxacum officinale* growth rate, total chlorophyll content, and comet assay were used to assess the physiological effects of ZnO- and CuO-NP exposure [102]. DNA damage was also evaluated. Plants were exposed through nebulizing dispersions of the nanoparticles. The exposure to 100 mg/L of ZnO-NPs caused the greatest amount of DNA damage. The two investigated nanoparticles' damage to DNA differed significantly from those of their bulk counterparts. Micrographs obtained using scanning electron microscopy (SEM) revealed a buildup of nanoparticles close to the stomata. The research proves that *T. officinale* is a viable bioindicator of the toxicity of airborne nanoparticles and that the comet assay has a high sensitivity for this purpose.

It was also determined how effective explanted tobacco plants are as an active biomonitoring system for NORM dust in the air. It was shown that tobacco plants are promising active bioindicators of airborne particle pollution due to their Po-210 or other atmospheric NORM concentrations [103]. Similar changes in leaf morphology or discoloration can signal indoor air pollution levels in *Chrysalidocarpus lutescens*, a popular indoor plant noted for its sensitivity to volatile organic compounds (VOCs) like formaldehyde, benzene, and trichloroethylene [104]. Spinach leaves are sensitive to ozone pollution, exhibiting characteristic bronzing or stippling on leaf surfaces when exposed to high tropospheric ozone levels [105].

5.3. Aquatic Plants for Water Quality

The most essential service ecosystems offer, along with the air we breathe, is the availability of clean water. Inland water ecosystems are threatened and fundamentally changed due to human activity. Because of this, inland water species have a higher chance of going extinct. According to reports, the extinction rate of freshwater animals may surpass that of terrestrial animals by up to five times in the future [106]. When there is a disturbance to the aquatic environment, people who are poor and reside in rural areas are frequently the ones who suffer the most. Pure freshwater is necessary to support life on Earth for all species. Although it is widely acknowledged that freshwater management must balance environmental requirements and development, attempts to apply a more integrated approach have only sometimes been successful.

The existence or lack of plants or other vegetative life can reveal crucial information about the environment's health. In an aquatic environment, for example, the total algal biomass serves as a valuable indication of organic pollution and nutrient loading, including nitrogen and phosphorus [107]. They can also function as metal accumulators or products of their metabolism. Plants are being used more and more as incredibly sensitive and useful sensors to detect and predict environmental disturbances. Elodea (*Elodea canadensis*), popularly referred to as waterweed, is frequently employed as a water quality indicator in freshwater environments. It is susceptible to variations in temperature, dissolved oxygen concentrations, and nutrient levels. Elodea population declines could be a sign of declining water quality [108]. A recent study used laboratory bioassay based on various endpoints of the aquatic plant Elodea canadensis (Elodea) to evaluate the cyto- and genotoxicity of bulk sediments from the Yenisei River. Samples of bottom sediment (BS) were taken both upstream and downstream of the Yenisei River's sources of chemical and radioactive pollution. Test findings showed that the following Elodea endpoints were sensitive to varying degrees to the quality of BS: percentage of aberrant cells, weight of shoots, length of shoots, mitotic index, and length of roots. The sediments with the highest levels of chemical and radioactive pollution most inhibited the toxicity endpoints for shoot and root length, while the genotoxicity endpoint—the percentage of cells in Elodea roots with abnormal chromosomes—was most responsive to these sediments. It is conceivable to draw a link between the potential existence of unknown toxicants and the strong responsiveness of Elodea endpoints to specific sediment sample quality [109]. According to the investigation's findings, BS laboratory contact testing can make use of *E. canadensis* as an indicator species.

A floating aquatic plant called water hyacinth (*Eichhornia crassipes*) can detect eutrophication and nutrient pollution in bodies of water. Thick water hyacinth mats may indicate hazardous algal blooms and an overabundance of nutrients. According to a different study, it is also a very good bioindicator of water contaminated by dangerous organic pollutants like neonicotinoids and endocrine disruptors. After a brief exposure, several organic pollutants, including bis (3-tert-butyl-4-hydroxy-6-methylphenyl) sulphide, pentabromodiphenyl ether, nitenpyram, acetamiprid, and di-n-hexylphthalate, were easily detected in the root system of *E. crassipes* by UHPLC-HRMS or GC-MS [110]. These findings provide fresh insights into the remediation of water contaminated by organic pollutants.

Dunaliella and *Synechococcus leopoliensis*, or blue-green algae, exhibit heavy metal pollution through accumulation and serve as reliable indicators of water pollution [111]. In *Anabaena cylindrica* under cadmium stress, cellular malformation, chlorosis, and a marked increase in heterocyst frequency have been observed [112]. *Pseudokirchneriella subcapitata* was used to assess pollution and is currently used to determine water pollution [113]. *Senedesmus subspicatus*, *Scapricornatum*, and *Chlorella vulgaris* can all be subjected to toxicity tests by monitoring the culture's volume, light intensity, and conditions [114].

5.4. Plants as Indicator for Soil Contamination

All environmental components, including soil, are crucial in reducing pollution, especially air and water since the soil is the largest natural filter for organic and inorganic contaminants. However, once the soil is saturated with contaminants, it can also pollute again. Toxic metals are defined as elements with an atomic number greater than 20, which are ductile, conductive, and ligand-specific and are persistent in the environment. There are some regional variations in the level of soil contamination. Toxic metals such as Cd, Pb, Hg, and As contaminated 26 million hectares of arable land in China, and each year, soil pollution contaminates about 12 million metric tonnes of grains, causing losses in economic value exceeding USD 3.2 billion [115–118]. A soil survey report published by the Chinese Ministry of Environmental Protection 2014 revealed that 16% of agricultural soils were contaminated, with inorganic contaminants accounting for 82.8% of the contamination [119]. To ensure safe food production, it is estimated that 137,000 km^2 of agricultural land (6.2%) in the European Union requires local assessment and remediation [120].

Clover (*Trifolium* spp.), one of the indicator plants for soil contamination, is widely used, particularly in areas with high heavy metal concentrations, such as lead, cadmium, and zinc [121]. The toxicity in the soil can be determined by changes in the growth and color of clover leaves. Through a process known as phytoextraction, sunflowers (*Helianthus annuus*) are well known for their capacity to collect heavy metals from contaminated soils. They are good indicators of soil pollution and possible candidates for phytoremediation projects due to their deep root systems and rapid growth. The sunflower plants were subjected to silver(I) ions at 0, 0.1, 0.5, and 1 mM concentrations over 96 h [122]. The focus was primarily on the observation of fundamental physiological parameters. The treated plants were discovered to have color changes, a lack of root hairs, and growth depression. The autofluorescence of anatomical features, such as lignified cell walls, might be used to identify changes in important shoot and root structures, namely vascular bundles and secondary thickening development. There were clear differences in the arrangement of the vascular bundles, the development of parenchymatic pith in the root centre, and the shrinkage of the phloem portion of the vascular bundles.

Additionally, the vitality of rhizodermal cells decreased as the concentration of silver(I) ions increased; these cells soon necrosed and were replaced by exodermis cells. Basic molecular markers of environmental stress were also looked at. As the dose of silver(I) ions was increased and the treatment duration extended, the overall protein content demonstrably decreased. Urease activity was the second biochemical parameter. When treated plants were compared to the control, it was discovered that the presence of silver(I) ions significantly increased the urease activity at all applied concentrations of this hazardous metal, proving that they can be utilized as bioindicator species. Plants concentrate metal elements in their parts that are above ground, indicating high concentrations of heavy metals in the soil. By changing the internal structures of leaves, for instance, and lowering the extensibility and relative water content of cell walls, cadmium often inhibits plant growth [123]. Pb can reduce leaf expansion, total chlorophyll concentration, and PSll electron transport efficiency [124]. Plant species and soil characteristics are linked to the attributes of Cd accumulation. According to a report, vegetables treated with soil treated with biosolids were less likely to accumulate Cd than vegetables grown in soil used for metalliferous mining and smelting. Research revealed that the levels of Cd in plants varied greatly between crops [125].

5.5. Sensitive Plants for Pesticide Contamination

Numerous pesticides are present in ambient air at amounts ranging from a few pg m^3 to several ng m^3, as a result of widespread pesticide applications [126]. In central France, for example, 41 pesticides have been found at amounts ranging from 0.1 to 117.3 ng m^3 [127]. A study found that the average concentrations of 20 pesticides in a rural station ranged from 1.63 to 117.01 pg m^3 and that the levels of contamination for 17 pesticides in one remote, one urban, and three rural sites ranged from 6.8 to 2 892 pg m^3 [128].

Monitoring of this high pesticide concentration needs to be performed. For example, the tomato (*Solanum lycopersicum*) is particularly sensitive to pesticide residues, and changes in fruit morphology, color, or taste can signal pesticide contamination in agricultural settings. Many plant species are found to be excellent pesticide monitors. Pesticide exposure levels can be determined and pesticide management strategies can be guided by monitoring tomato plants. Moreover, pesticide contamination, especially from insecticides and herbicides, can affect beans (*Phaseolus vulgaris*). Pesticide stress can be indicated by symptoms like leaf curling, wilting, or stunted growth, which can threaten crop health and environmental quality [129].

6. Challenges and Opportunities

Utilizing plants as bioindicators has advantages and disadvantages. One difficulty is the variability in response, as different plant species react to environmental toxins differently. It is not easy to choose the best species for a given study. Confounding factors present another difficult aspect of using plants as bioindicators. The response of plants to toxins can be influenced by environmental factors like temperature, humidity, and soil composition, making it challenging to separate the toxins' effects. Interpreting the results presents another difficulty because it calls for knowledge and can be complicated. It can be difficult to react to toxins. Different stressors can produce similar symptoms, and complex interactions may arise between multiple stressors.

Furthermore, conducting studies using plants as bioindicators can take time and resources, especially for long-term monitoring initiatives. Additionally, there are some opportunities for using plants as biomonitoring tools. Due to their propensity to exhibit outward symptoms of stress or damage before more serious environmental effects, plants can act as an early warning system for environmental pollutants. Also, employing plants as bioindicators can be more affordable than conventional ecological monitoring methods, particularly for large-scale studies encompassing large areas. Additionally, plants can be used to monitor biodiversity because analyzing how species react to environmental pollutants can reveal important information about an ecosystem's general well-being and biodiversity. Because they can be found in a wide range of habitats across the globe, plants are versatile bioindicators for a wide range of environmental toxins, including soil, water, and air pollutants. With the help of plant-based bioindicators, environmental conditions can be better understood overall and in conjunction with other monitoring techniques like chemical analysis and remote sensing.

7. Future Directions

Environmental toxins pose a serious threat to ecosystems, so it is necessary to monitor them properly. Plant bioindicators can be used as an eco-friendly indicator of toxins in our ecosystem, but this requires further research. Although various bioassays have been developed to test the presence of toxins, they still need improvement. The integration of precision monitoring technologies, including transcriptomics, proteomics, and metabolomics, offers improved resolution in interpreting molecular reactions to toxins. Moreover, combining imaging and remote sensing technologies can strengthen temporal and spatial monitoring capabilities, allowing real-time surveillance over large areas. The advancement of portable sensors, supported by sophisticated machine learning and bioinformatics algorithms, highlights a paradigm change in the direction of quick, on-site detection techniques. Furthermore, strategic policy integration combined with community-driven science initiatives has the potential to increase the translational impact of research on plant bioindicators. It urges a concentrated effort to utilize cutting-edge technologies and promote interdisciplinary partnerships to advance the study of plant tissue bioindicators into new areas of highly influential environmental science.

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