

Impact of Environmental Pollution on Plant Growth and Development

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Alka Singh

Abstract

Environmental Pollution is any unfavorable change in constituent of environment, it drastically affect the Human, Animal and Plant growth because they are not be able to easily cope with drastically changing environment. Environmental contamination resulting from human activity has gained international attention. Globally implemented policies and legislative modifications pertaining to air, water, and soil pollution necessitate ongoing consideration and the creation of fresh methods for damage mitigation. Hazardous compound releases that are not desired into the environment are mostly caused by mining, industry, urbanization, and specific agricultural activities, in addition to inappropriate waste disposal. The growth and physiology of plants, especially those with agricultural value, can be adversely affected by these pollutants, such as trace elements, which can have detrimental ecological and economic effect.

There are several visible and unseen effects on the various plant species caused by the wide variety of contaminants and the rapidly increasing quantity of synthetic compounds. The main ways by which contaminants from the air, water, soil, and other sources pierce plants are through the stem, leaves, flowers, roots, or the entire surface. These artificial or naturally occurring contaminants interact with different plant species, changing their molecular, physiological, biochemical, and growth processes. In this chapter, we mainly deal with how environmental pollution affects plant growth.

Keywords: *Environmental pollution, Plant growth, Plant stress response, Contaminants*

Alka Singh

Assistant Professor, Dept. of Botany, Navyug Kanya Mahavidyalaya Rajendra Nagar, Lucknow

Book Name : Interdisciplinary Pathways towards Sustainable Development

Pub:Anu Books. ISBN:9789378470097, DOI:10.31995/Book.AB364-J226.Ch.18

1. Introduction

Plants are essential components of ecosystems and play a critical role in maintaining environmental balance through oxygen production, carbon sequestration, and food supply. However, rapid industrialization, urbanization, agricultural intensification, and improper waste disposal have significantly increased environmental pollution worldwide. Pollutants released into the air, water, and soil adversely affect, plant morphology, physiology, growth, and overall productivity [1]. Environmental contaminants such as sulfur dioxide (SO₂), nitrogen oxides (NO_x), ozone (O₃), heavy metals, pesticides, industrial effluents, and plastic particles interfere with normal metabolic activities and disrupt essential physiological processes in plants. Recent studies further shows that emerging pollutants, including nanoparticle, micro plastics, pharmaceutical residues, and industrial by-products negatively influence plant growth, nutrient uptake, and soil microbial activity [2, 3]. The major types of pollutants and their effects on plant growth are summarized in **Table 1**.

Table 1: Effects of Different Types of Pollution on Plant Growth

Pollution Type	Major Pollutants	Source of Pollution	Impact on Plant Growth	Visible Symptoms in Plants
Air Pollution	SO ₂ , NO _x , ozone, particulate matter, carbon monoxide	Industries, vehicles, thermal power plants, fossil fuel burning	Reduces photosynthesis, damages chlorophyll, slows growth, decreases crop yield	Yellowing of leaves, leaf burn, premature leaf fall, stunted growth
Water Pollution	Heavy metals, pesticides, detergents, industrial waste, sewage	Industrial discharge, agricultural runoff, domestic waste	Affects nutrient uptake, damages roots, reduces seed germination and metabolism	Wilting, root decay, poor flowering, reduced growth
Soil Pollution	Chemical fertilizers, pesticides, heavy metals, plastic waste	Excessive agrochemicals, industrial dumping, mining	Reduces soil fertility, harms soil microbes, affects root development	Poor root growth, weak plants, low productivity
Noise Pollution	High-frequency sound waves, vibrations	Traffic, machinery, industries, construction	Disturbs metabolic activities and seed germination; may reduce growth rate	Delayed germination, reduced leaf size, slower growth
Light Pollution	Artificial light, excessive night illumination	Street lights, industries, buildings, advertisements	Disrupts photoperiodism, flowering, and circadian rhythm	Delayed flowering, abnormal growth, reduced fruiting
Acid Rain	Sulfuric acid (H ₂ SO ₄), nitric acid (HNO ₃)	Emission of SO ₂ and NO _x from industries, vehicles, thermal power plants leading to acid formation in atmosphere	Lowers soil pH, damages leaf tissues, reduces nutrient availability, inhibits photosynthesis and overall plant growth	Leaf chlorosis, leaf burn, necrosis, reduced growth, premature leaf fall
Emerging Pollutants	Microplastics, nanoparticles, pharmaceutical residues, industrial by-products	Plastic degradation, nanotechnology industries, sewage water, hospital waste, industrial discharge	Disturb soil and water quality, affect nutrient uptake, photosynthesis, enzyme activity, and plant metabolism	Stunted growth, chlorosis, poor germination, root damage, reduced biomass

The response of plants to environmental pollution is highly complex and depends on several biological and environmental factors. Plant tolerance and sensitivity, vary according to species and genetic composition, pollutant concentration, type and combination of pollutants, developmental stage of the plant, and biotic stresses such as diseases and insect infestation [4]. In general, gymnosperms are considered more sensitive to air pollution than angiosperms; however, the level of resistance and susceptibility varies considerably within each plant group [5]. Mechanisms include avoiding pollutant uptake, tolerance to toxic effects, metabolic conversion of pollutants into less toxic chemicals, and dilution of pollutants by fast redistribution to various plant parts are the main causes of plant resistance to pollution [6]. These adaptive mechanisms influence the ability of plants to survive, adjust, and maintain productivity under polluted environmental conditions.

Certain plant species in forest ecosystems may grow even under severe pollution stress. This may be due to their stronger competitive advantage. They can compete other species during ecological succession. When exposed to a certain amount of an air contaminant, young seedlings are typically more vulnerable than older seedlings or mature trees. Nonetheless, canopy trees in a forest stand are typically more severely impacted than understory trees, largely due to the tall trees' filtering effect, which reduces the amount of pollutants that reach the smaller trees. Broadleaf trees are especially vulnerable to SO₂ in the younger, fully expanded leaves and those that are almost fully extended. Small, growing leaves are the least sensitive, whereas older leaves are less sensitive than others. The juvenile needles of gymnosperms are extremely delicate. Before, during, and after a pollution incident, environmental conditions can significantly modify the impact of pollutants on plant systems. Changes in temperature, humidity, light intensity, and soil moisture influence plant metabolism as well as stomatal aperture, thereby affecting the uptake and internal distribution of pollutants.

Similarly, exposure to ozone (O₃) in broadleaf species leads to visible foliar injury such as chlorotic stippling, reduced chlorophyll content, and premature senescence, ultimately lowering photosynthetic efficiency and plant productivity. Likewise, nitrogen dioxide (NO₂) inhibits growth and reduces carbon assimilation in actively growing leaves by interfering with stomatal functioning and chlorophyll synthesis [1].

In addition, particulate matter (PM) deposition on leaf surfaces of broadleaf trees can physically block stomata, thereby reducing gas exchange

and transpiration rates, which negatively impacts overall plant metabolism [7]. Heavy metals such as lead (Pb) and cadmium (Cd), when accumulated in soil, are readily taken up by plant roots and transported to leaves, where they interfere with nutrient balance, induce oxidative stress, and cause chlorosis and necrotic symptoms in young tissues [8]. Fluoride (F) pollution is also known to be highly phytotoxic to broadleaf species, often causing marginal leaf burn, tip necrosis, and reduced leaf expansion.

These responses indicate that broadleaf trees, due to their large leaf surface area and active metabolic processes, are highly sensitive bio indicators of air and soil pollution, and their physiological responses can effectively reflect environmental quality conditions. The severity of pollution effects is further influenced by interactions between pollutants and biological agents. For example, the presence of fungal pathogens or insect herbivory can either increase plant susceptibility or amplify damage caused by pollutants, while in some cases pollutant exposure may weaken host resistance, leading to higher disease incidence and increased frequency of infection [9]. Thus, the overall impact of pollution on plants is not only species-dependent but also strongly regulated by environmental conditions and biotic interactions. Collectively, these interactions demonstrate the complex nature of plant responses to environmental stress, as illustrated in **Figure 1**, which shows its impact on plant growth and physiological performance.

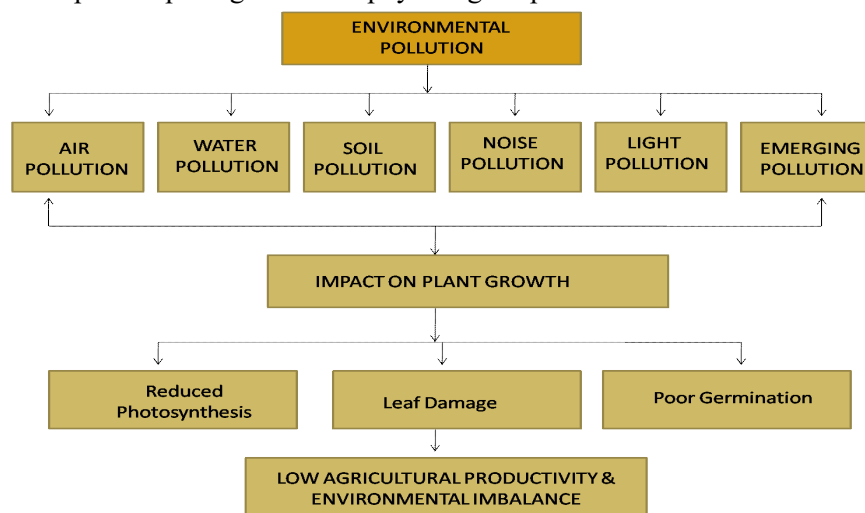


Figure 1: Effect of environmental pollution on plant growth and physiological performance.

2. Why are Plants Sensitive to Different Forms of Pollution?

Since they are living things, plants rely on a variety of environmental elements to survive. They include the right amount of heat and light, nutrition supplies, water, air, and physical space, as well as the ideal growing medium (various kinds of soil or water). Through their roots and leaves, plants absorb essential nutrients and other substances from the soil and surrounding environment for their growth and reproduction. Then, plants employ these materials to construct bodily tissues and provide energy to body cells, so they can function. As plants cannot move like animals, they rely on internal processes to utilize all absorbed materials. As a result, even minor environmental disturbances can significantly affect plant growth and metabolism their physiological functions and overall growth.

Every plant will be impacted differently depending on a variety of characteristics that vary from location to location or between different plant species, such as soil type, pollutant concentration, plant age, temperature, and season. When contaminants and other materials that do not normally exist in the environment come into touch with plants or are absorbed by plants, it is essentially considered plant pollution. In this sense, soil, water, or the air can all pollute plants. The impact of plant contamination are-

2.1 Damage to Leaf Structure and Function: Contaminants in air, water, and soil can damage leaf tissues. Ozone and other ground-level pollutants physically harm plant leaves, resulting in chlorosis or an unusual yellowing of the leaves. As a result, there is a lack of chlorophyll, which prevents the plant from producing its own food or energy.

2.2 Delay in Flowering and Reproductive Development: When a plant is under stress, it will exhaust all of its resources to fend off the threat and live. Pollutants such as heavy metals, gases, and contaminated water interfere with hormonal balance and metabolic processes required for flowering. This leads to delayed initiation of flowering, reduced flower formation, and in some cases failure to flower. As a result, the reproductive success and yield of plants are significantly reduced.

2.3 Root System Damage and Impaired Growth: Toxic substances such as heavy metals, pesticides, and industrial wastes accumulate in the soil and are absorbed by roots. This leads to damage of root tissues, reduced root growth, and impaired water and nutrient uptake. As a result, the overall growth and stability of the plant are negatively affected.

2.4 Stomatal Dysfunction and Reduced Gas Exchange: Stomata are small pores on leaves that serve as points of gas exchange between the plant and the surrounding environment. When gas exchange is hampered by pollutants such as SO₂, NO₂, and ozone, plant stomata may shrink or become dysfunctional, which slows down photosynthesis. This ultimately decreases photosynthetic efficiency and affects overall plant growth.

Furthermore, harmful substances like pesticides, heavy metals, and industrial pollutants interfere with plants' ability to absorb nutrients and maintain water balance, which causes oxidative stress, enzyme inhibition, and cellular damage. In extreme circumstances, contamination may have an impact on plant reproduction and seed germination, which would ultimately lower ecosystem stability and biodiversity. Additionally, contaminants that build up in plant tissues may find their way into the food chain and endanger the health of both humans and animals. In general, ecosystem health, environmental sustainability, and agricultural output are all adversely affected by plant contamination.

3. Impact of Air Pollution on Plant Growth

3.1 Gaseous Pollutants

Air pollution can come from a variety of sources, including factory smoke, vehicle emissions, and gas leaks from the manufacture of plastic and paint. Air pollution can harm a wide variety of plants, including millions of tree species and our food crops. This type of air pollution is mainly caused by atmospheric gases such as carbon oxides, sulfur oxides, and nitrogen oxides. There are numerous ways to view the harm done to plants. The following are obvious indicators that air pollution is harming plants:

- Leaf yellowing (chlorosis) due to reduced chlorophyll content.
- Leaf necrosis or tissue damage caused by toxic gases like SO₂ and ozone.
- Stunted plant growth resulting from impaired photosynthesis.
- Premature leaf fall (defoliation) under severe pollution stress.
- Reduced flowering and yield, affecting overall plant productivity.
- Color changes such as bronzing, reddening, mottling, and chlorosis.

Air pollution rarely exists singly. Rather the environment contains a mixture of gaseous and particulate air pollutant [10]. In many parts of Western Europe, it is more useful to study the combined effect of SO₂ and NO₂ on

vegetation, than to study the independent effect of these pollutants [11]. These combinations can act simultaneously or sequentially [12], and their effects are often synergistic [13, 14], additive [15] or antagonistic [16]. Among the important factors influencing plant responses to pollutant mixtures are the concentration of each gas in the mixture with respect to the injury thresholds of the individual pollutants, the relative proportion of these gases, whether there is simultaneous or intermittent application of the combined pollutant stress; and the age and physiological state of the plant [10, 17-18].

Plants are also being harmed by the holes that pollution has made in the ozone layer of the atmosphere. The plants are harmed by excessive UV light entering these apertures in the upper atmosphere, which results in alterations to their morphology, delayed developmental phases, and altered nutrition distribution inside the plants.

Ozone harms plants by blocking photosynthesis and blocking stomata, which limits respiration and stunts plant growth. As a result, the lower atmosphere is also impacted. The ground-level ozone molecule is created when volatile organic compounds and nitrogen oxides combine. The primary air contaminant is ground-level ozone. Some air pollutants, plant diseases, soil moisture, and other environmental stressors can all make the damage caused by ozone to plants worse.

3.2 Oxidative Stress in Plants (ROS Formation)

Prolonged exposure to air pollutants induces excessive production of reactive oxygen species (ROS), leading to oxidative stress that damages cellular components such as lipids, proteins, and DNA. This results in enzyme dysfunction, disruption of metabolic pathways, and a consequent decline in plant growth and yield. In extreme circumstances, air pollution also impairs the plant's defensive systems, making it less resistant to infections and more vulnerable to other environmental pressures. These cumulative effects eventually upset the equilibrium of the ecosystem and drastically lower agricultural yield [2, 19].

3.3 Particulate Matter and Plant Damage

Particulate matter (PM) pollution is a relatively recent Anthropocene phenomenon driven by rapid industrialization and urbanization worldwide. Particulate matter (PM) air pollution consists of tiny dust particles and pollutants suspended in the atmosphere. These particles are released from vehicles, industries, construction activities, and the burning of fossil fuels.

Acute and chronic damage are the two primary direct harm types that PM pollution can inflict on plants. Acute injury is caused by a short exposure to a high concentration of gas and is characterized by obvious signs on the foliage, most frequently in the form of necrotic lesions. While this kind of harm is rather obvious, chronic injury is considerably harder to spot; it develops over time from exposure to decreasing gas concentrations.

Even though plants have certain stress-tolerant mechanisms, PM and dust deposition significantly harms plants by blocking sunlight and clogging leaf stomata, inhibiting protein synthesis which reduces photosynthesis and plant growth. It also increases their vulnerability to damage from insects and pathogens. Plants' metabolic reactions to PM pollution can be understood as potentially adaptive modifications in their physiology, biochemistry, and genotoxicity.

4. Impact of Soil Pollution On Plant Growth

Soil or land pollution has a significant negative impact on plant growth, development, and productivity. Contaminants such as heavy metals (lead, cadmium, and mercury), excessive fertilizers, pesticides, industrial waste, inappropriate waste disposal, unlawful dumping, oil spills, and plastic residues alter the physical, chemical, and biological properties of soil. As a result, beneficial soil microbes are disrupted, nutrient availability becomes unbalanced, and soil fertility is decreased. These chemical sources degrade soil quality by infiltrating it and depleting essential nutrients.

Plants grown in polluted soil often show poor root development, reduced water and nutrient uptake, and stunted growth. Toxic substances interfere with enzymatic activity and photosynthetic processes, causing oxidative stress and cellular damage. Furthermore, the accumulation of heavy metals in plant tissues can result in necrosis, chlorosis, and decreased crop yield. Seed germination and plant reproduction are negatively impacted by severe soil pollution, which eventually lowers biodiversity and jeopardizes ecosystem stability and food security [2, 4].

5. Impact of Water Pollution On Plant Growth

Water pollution has a significant negative impact on plant growth and development. It can originate from various sources such as industrial effluents, domestic sewage, pesticides etc. and disrupt physiological and biochemical processes in plants. These pollutants reduce seed germination, inhibit root and shoot growth, and decrease photosynthetic efficiency. As

a result, overall biomass production and crop yield are adversely affected. Research has demonstrated that contaminated irrigation water can cause harmful compounds to build up in plant tissues, further affecting growth and metabolism [20]. Water pollution is also associated with oxidative stress, reduced chlorophyll content, and cellular damage in plants [21].

6. Impact of Acid Rain On Plant Growth

Acid rain is among the harmful contaminants that affect plants. When atmospheric water and nitrogen and sulfur dioxide oxides combine, acid rain is produced. When acid rain falls on vegetation, it lowers the pH of leaf surfaces and soil, disrupting normal physiological and biochemical processes in plants.

On leaves, acid rain damages the waxy protective layer, making plants more vulnerable to water loss, pathogen attack, and pollutant entry. It also reduces chlorophyll content, leading to chlorosis, reduced photosynthesis, and stunted growth. On a cellular level, acid rain causes enzyme inhibition and increases oxidative stress, which further weakens plant metabolism. The process of gas exchange is also altered as stomatal function is affected, resulting in reduced CO₂ uptake and impaired transpiration. Acid rain impairs plant metabolism at the cellular level by increasing oxidative stress and inhibiting enzymes [22, 23].

The quality of soil is impacted by acid rain as well. In the soil, acid rain leaches essential nutrients such as calcium, magnesium, and potassium while increasing the solubility of toxic metals like aluminum, which can damage root systems and inhibit nutrient uptake. Over time, these effects result in reduced plant productivity, poor seed germination, and decline in forest and crop health. Severe acid rain exposure can ultimately lead to forest degradation and loss of biodiversity [24]. The nutrients and minerals that plants require also remove from soil by acid rain, which also contaminates the groundwater.

7. Impact of Noise Pollution On Plant Growth

Although plants do not have a nervous system like animals, increasing research shows that noise pollution can still indirectly affect plant growth, physiology, and development. Noise from traffic, industries, and urban activities mainly influences plants by disturbing pollinators and other organisms that are essential for plant reproduction.

One major impact of noise pollution is the reduction in pollination efficiency. Plants use sound waves to detect predators in their immediate vicinity, which helps them activate their defense mechanisms. Many pollinators such as bees and birds rely on sound and environmental cues for communication and movement. Excessive noise can disturb their behavior, leading to reduced visitation rates to flowers and ultimately lowering seed and fruit production. This negatively affects plant reproductive success and biodiversity.

In addition, continuous noise exposure can create stress conditions in the surrounding environment, indirectly affecting plant physiological processes such as growth rate, hormone balance, and resource allocation. Studies also suggest that plants in noisy environments may experience reduced regeneration and altered community structure due to disrupted ecological interactions. Plant reactions to noise pollution can differ depending on how the surrounding biological community changes; some species may exhibit improved growth performance while others may have decreased fitness under the same circumstances [25]. Studies have shown that anthropogenic noise can reduce reproductive success in plants by hindering effective pollinator activity and lowering crop yield [26].

Over time, these effects can contribute to changes in ecosystem stability and reduced plant diversity in urban and industrial areas. Overall, noise pollution contributes to reduced plant reproductive success, altered ecosystem interactions, and declining biodiversity in urban and industrial environments [27, 28].

8. Impact of Light Pollution On Plant Growth

Light pollution, caused by excessive or artificial lighting in urban and industrial areas, disrupts the natural light–dark cycles that regulate plant growth and development. Plants rely on photoperiodism (day length) to control essential processes such as flowering, seed germination, dormancy, and seasonal growth patterns. Exposure to artificial night light can interfere with these biological rhythms, leading to altered flowering times, delayed dormancy, and irregular growth patterns. It also affects photosynthesis and respiration cycles by disturbing the balance between day and night metabolic activities. In some species, prolonged exposure to artificial light can reduce reproductive success by affecting pollination timing and flower development [29-31].

Furthermore, light pollution can influence plant hormone regulation, particularly phytochrome-mediated responses, which control stem elongation, leaf expansion, and stress adaptation. Over time, these disruptions can lead to reduced plant fitness, changes in species composition, and altered ecosystem dynamics in urban environments [32]. Light pollution have impacts on ecological communities by directly affecting key species. As we know that all species depend on each other for food, shelter and reproduction, so effect of light pollution on one species have consequence on other species also. The pollution from light raising the illumination surrounding them might make it impossible for them to ever blossom and thus procreate. This impacts not just the cactus, but also the species that pollinates them. Strongly perfumed plants with white blossoms are usually pollinated at night.

9. Impact of Emerging Pollutants On Plant Growth

Emerging pollution refers to newly identified or increasingly significant contaminants that were not traditionally recognized as major environmental threats but are now known to affect ecosystems and plant health. These include microplastics, nanoparticles, pharmaceutical residues, and other industrial by-products that persist in soil, water, and air [33].

Microplastics and nanoplastics in soil can alter soil structure, reduce water retention, and interfere with root development, ultimately affecting plant growth and nutrient uptake [34]. Similarly, designed nanoparticles may penetrate plant tissues and interfere with cellular functions, resulting in metabolic imbalance, oxidative stress, and decreased photosynthetic efficiency [35]. Pharmaceutical and chemical residues present in water and soil can further impact plant physiology by altering hormonal regulation and enzyme activity [36].

According to recent research, these new contaminants may also have an impact on soil microbial communities, which are essential for the cycling of nutrients and the health of plants. As a result, plant growth, productivity, and ecosystem stability may be significantly compromised due to long-term exposure to such contaminants [37].

10. Conclusion

Environmental pollution, including air, water, soil, light, noise, and acid rain has a significant negative impact on plant growth and development. Pollutants such as particulate matter, gaseous emissions, and

toxic chemicals disrupt physiological and biochemical processes in plants. These stresses reduce photosynthesis, impair nutrient uptake, damage cellular structures, and ultimately decrease plant productivity. Therefore, safeguarding plant health and preserving ecological balance require an understanding of the mechanisms behind pollution-induced stress.

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