10. ULUSLARARASI ÖĞRENCİ SEMPOZYUMU

International Student Symposium

FEN VE MATEMATİK

BİLDİRİLER KİTABI

3

PROCEEDINGS BOOK

SCIENCE AND MATHEMATICS

28 Aralık
İSTANBUL TEKNİK ÜNİVERSİTESİ
2024 / İSTANBUL

"Bu proje T.C. İçişleri Bakanlığı Sivil Toplumla İlişkiler Genel Müdürlüğü tarafından desteklenmektedir."

T.C. İÇİŞLERİ BAKANLIĞI
SİVİL TOPLUMLA İLİŞKİLER
GENEL MÜDÜRLÜĞÜ

10. ULUSLARARASI ÖĞRENCİ SEMPOZYUMU
BİLDİRİLER KİTABI - 3
10th INTERNATIONAL STUDENT SYMPOSIUM
PROCEEDINGS BOOK – 3

SCIENCE and MATHEMATICS
FEN ve MATEMATİK

Tasarım / Graphic Design
Cüret Karakaş
UDEF

ISBN: **978-625-7480-40-6**

Yayım Tarihi / Publication Date
İstanbul, 2025

Yayınevi Bilgileri / Publisher

ULUSLARARASI ÖĞRENCİ DERNEKLERİ FEDERASYONU (UDEF)
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İÇİNDEKİLER

Comparative Analysis of Edible Mushroom Species in Türkiye and Morocco: Ecological Impacts and Species Distribution

Amal Belaid[1], *Sinan Alkan*[2], *Gıyasettin Kaşık*[3]

Abstract

This study provides a comparative analysis of edible mushroom species across Morocco and Türkiye, with a focus on species richness, ecological distribution, and the environmental factors shaping their growth patterns. Both countries host diverse ecosystems that support a wide range of macrofungal species, integral to local diets and traditional medicinal practices. The primary aim of this research is to identify both shared and unique edible mushroom species within these regions and to assess how ecological variables such as climate, altitude, and soil composition influence their distribution. Through comprehensive field surveys, systematic sample collection, and laboratory analyses, the study catalogs these species and compares findings from Morocco and Türkiye to elucidate how environmental differences affect species diversity. The results reveal notable overlaps in certain species while highlighting region-specific mushrooms that mirror the distinct ecological landscapes of each country. This research provides valuable insights into the ecological roles and distribution patterns of edible mushrooms, supporting efforts in conservation and the sustainable utilization of these species.

Keywords : Edible mushrooms, Morocco, Türkiye, species distribution, ecological factors.

Discipline : Mycology, Ecology.

Introduction

The worldwide mushroom industry has grown at a rapid rate since the late 1990s (Fig.1)[11]. The earliest reports of mushroom consumption are from Spain (18,700 years ago), China (5,000 to 6,000 years ago),and Egypt (4,600 years ago)[12], Edible mushrooms are valuable functional foods with high essential amino acids, unsaturated fatty acids, protein, carbohydrates, dietary fiber, minerals and vitamins, and low fat and energy content[13]. Approximately 3000 species of wild mushrooms can be consumed directly, and approximately 20 species are commercially cultivated. [14], China is the leading producer country in terms of mushroom production. According to 2013 data, 85% of the world's total cultivated edible mushroom supply was made up of *Lentinula, Pleurotus, Auricularia, Agaricus* and *Flammulina* genera. In the same year, per capita cultivated mushroom consumption worldwide exceeded 4.7 kg/year[5].

Five main genera account for approximately 85% of the world's mushroom supply (Fig. 2). *Agaricus* (primarily *A. bisporus*, with some *A. brasilensis*) is the dominant genus, representing about 30% of global cultivated mushroom production. *Pleurotus*, a close second with 5 to 6 cultivated species, accounts for around 27% of total output. *Lentinula edodes* (shiitake) contributes approximately 17%.

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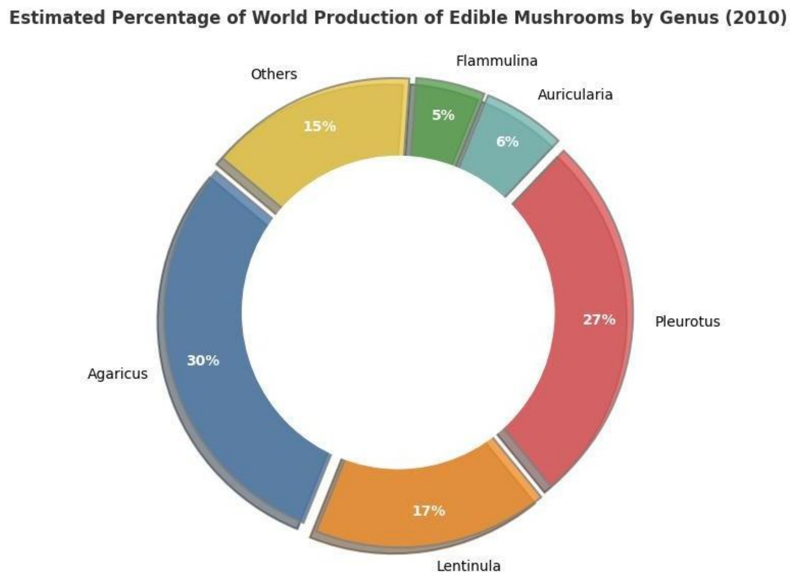
The remaining two genera, *Auricularia* and *Flammulina*, are responsible for about 6% and 5% of the global volume, respectively [11].

Figure 2: Estimated percentage of world production of edible mushrooms by genus in 2010



In Türkiye, the most cultivated species were reported as *Agaricus* species, *Pleurotus* species and *Lentinula edodes* species. In Türkiye, per capita cultivated mushroom consumption in 2014 was 579.2 g/year[15]. Morocco, on the other hand, is beginning to exploit the natural resources of edible mushrooms, particularly by focusing on naturally occurring local species, such as *Lactarius deliciosus* and *Morchella esculenta*, which are particularly popular in some mountainous regions[1]. The ecological diversity of these two countries supports a wide variety of edible fungal species, but it also poses challenges in terms of conservation and sustainable management[16].

Türkiye is home to a notable biodiversity of wild edible mushrooms, especially in the Black Sea and Anatolian regions, where species such as *Cantharellus cibarius* and *Morchella esculenta* are particularly valued for their nutritional and gastronomic qualities[17]. Morocco, on the other hand, has a rich fungal biodiversity in diverse regions such as the Rif and Atlas, offering distinct edible species, including *Lactarius deliciosus* and *Tricholoma terreum*, which are traditionally consumed in several rural communities [1]. However, unlike Türkiye, Morocco mainly exploits wild mushrooms, with little infrastructure for intensive cultivation, which limits the accessibility of mushrooms to the domestic market [3]. This difference highlights a more wild and traditional approach to mushroom consumption in Morocco compared to the organized production model in Türkiye. The differences in biodiversity between the two countries are explained by ecological and climatic variations, favoring a unique ecosystem for each region. In Türkiye, the variety of biomes, ranging from temperate forests to arid mountains, allows for a proliferation of adaptive and edible fungal species [18]. In Morocco, mushroom biodiversity is particularly influenced by Mediterranean and mountain microclimates, favoring a diversity of endemic species that are often subject to seasonal harvests [4]. However, both countries face common challenges in terms of conserving natural habitats and developing sustainable practices to ensure the sustainability of these fungal resources.

In the face of these challenges, a collaboration between Morocco and Türkiye could allow the exchange of cultivation practices and conservation knowledge. The establishment of a network to study and protect edible mushrooms could support the adoption of conservation and sustainable development strategies [19]. By combining the strengths of structured production in Türkiye and Morocco's natural approach, it would be possible to strengthen food security while preserving local fungal diversity.

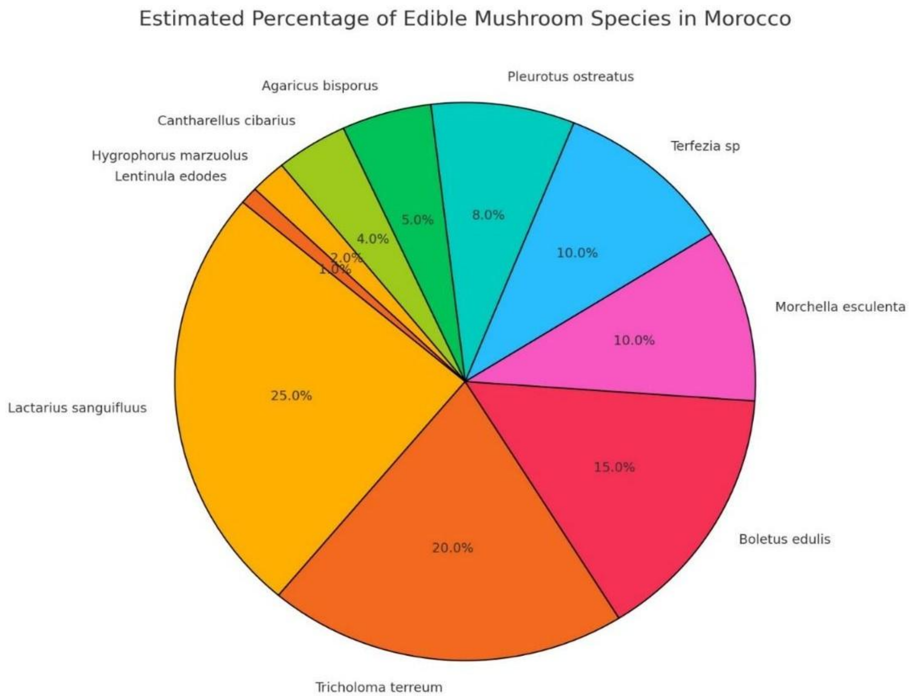
This comparison of mushroom resources between Türkiye and Morocco aims to encourage collaborative efforts for species preservation and the development of new sustainable cultivation practices [19].

Edible Mushrooms in Türkiye and Morocco

Edible Mushrooms in Morocco

In Morocco, the diversity of edible mushrooms is vast, with several species sought after for their taste qualities and nutritional value. Among the most popular edible mushrooms are *Lactarius deliciosus* and *Tricholoma terreum*, which represent about 45% of wild mushroom consumption in rural areas[1]. *Boletus edulis* and *Agaricus bisporus* are also consumed, although their proportion is lower, with about 20% of total consumption, mainly in areas close to the Rif and Atlas Mountains [2]. Recent data show that about 35% of Moroccan rural families consume wild mushrooms regularly, while this figure drops to about 10% in urban areas, due to more limited access and lesser knowledge of these species [3]. Among the endemic species in Morocco, *Morchella esculenta* (morel) is highly prized, but its harvest is regulated in some areas to avoid overexploitation; This species represents about 8% of total consumption [4]. The majority of mushrooms consumed in Morocco come from wild harvesting, with few commercial cultivation structures, which limits their availability in national markets. Imported mushrooms, although accessible in large cities, represent about 5% of total consumption, with a preference for European species such as *Pleurotus* [5]. The table below provides a detailed overview of the key edible mushroom species consumed in Morocco, with respective consumption percentages based on cultural preferences and regional availability.

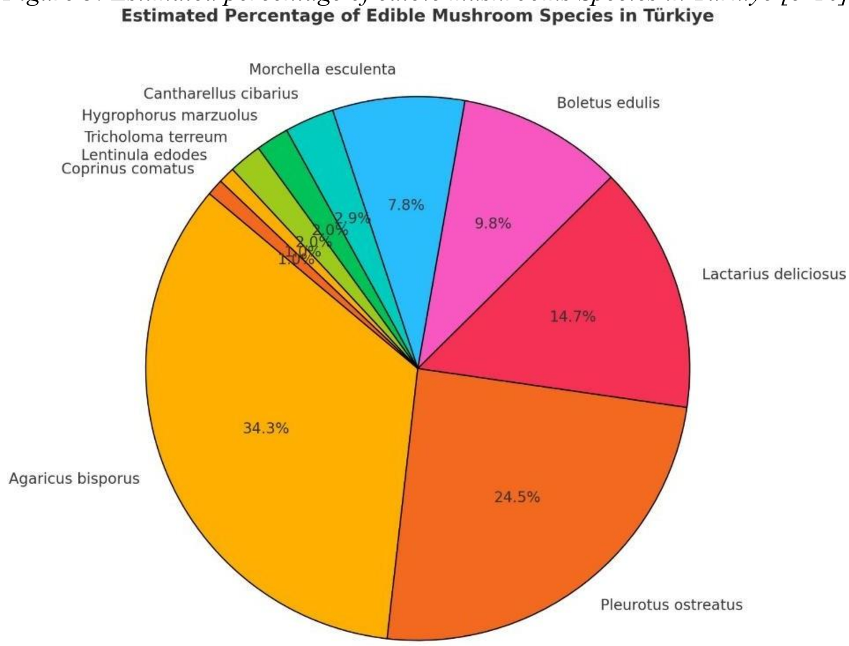
Figure 3: Estimated percentage of edible mushrooms Species in Morocco[1-4]



Edible Mushrooms in Türkiye

In Türkiye, a diverse array of edible mushrooms is consumed, reflecting the country's rich mycological heritage. The most widely consumed species is *Agaricus bisporus*, commonly known as the button mushroom, accounting for approximately 35% of mushroom consumption, primarily due to its widespread cultivation and popularity in urban markets [5, 6]. Following this, *Pleurotus ostreatus,* or oyster mushroom, represents about 25% of consumption, prized for its culinary versatility and ease of cultivation [7, 8]. Another significant species is *Lactarius deliciosus*, known as the saffron milk cap, which makes up around 15% of the total consumption, particularly valued in rural areas for its distinctive flavor [5, 9]. The highly sought-after *Boletus edulis*, or porcini, accounts for about 10% of the mushroom market, often featured in traditional dishes due to its rich taste[6, 9]. Additionally, *Morchella esculenta* (morels) are harvested in spring, comprising approximately 8% of consumption. [8, 10] Lesser-known varieties include *Cantharellus cibarius* (chanterelles) at 3%, *Hygrophorus marzuolus* at 2%, and *Tricholoma terreum* also at 2%, with each valued for their unique culinary properties[5, 10]. Cultivated varieties like *Lentinula edodes* (shiitake) and *Coprinus comatus* (shaggy mane) contribute about 1% each, showcasing the growing market for these mushrooms in urban areas[6, 8]

Figure 3: Estimated percentage of edible mushrooms Species in Türkiye [5-10]



Comparison of Edible Mushroom in Türkiye and Morocco

Comparison of Edible Mushroom Species Percentage Distribution in Türkiye and Morocco

The chart above compares the distribution percentages of various edible mushroom species in Türkiye and Morocco.

Figure 4: Edible Mushrooms Species [statistics]

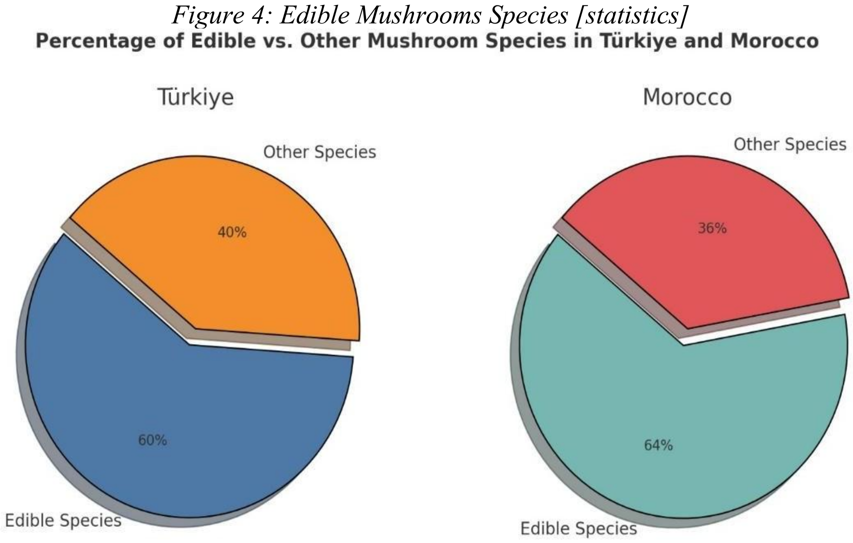


Figure 5: Comparison of Edible Mushroom Species Percentage Distribution in Türkiye and Morocco

In Türkiye, *Agaricus bisporus* (kültürmantarı(Sesli et al., 2020)) is the most widely consumed, accounting for 35% of the market due to its accessibility and popularity in urban areas, whereas in Morocco, it constitutes only 5% of edible mushrooms, reflecting lower demand [5]. *Pleurotus ostreatus* (oyster mushroom) also shows a high share of 25% in Türkiye, largely driven by its versatile use in Turkish cuisine [20]. Conversely, this mushroom represents only 8% of Morocco's market, where *Lactarius deliciosus* is more popular, making up 25% of edible mushroom consumption, especially in rural areas [21].

Both countries highly value *Boletus edulis* (porcini), constituting 10% in Türkiye and 15% in Morocco, due to its rich flavor profile in regional dishes [22]. Additionally, *Terfezia sp.* (desert truffle) holds a unique 10% share in Morocco, prized as a delicacy in semi-arid areas, while it is not common in Türkiye [23].

Biodiversity and Distribution of Edible Mushrooms in Morocco and Türkiye

Morocco and Türkiye showcase rich biodiversity in edible mushrooms, influenced by varied climates and ecosystems. Morocco's mushroom diversity is particularly high in mountainous regions like the Rif and Atlas Mountains, where species such as *Lactarius deliciosus* and *Russula cyanoxantha* are commonly found[24]. These regions' unique ecological conditions contribute to the growth of highly prized desert truffles*, Terfezia sp*., in Morocco's semi-arid zones[23]. Conversely, Türkiye's diverse climates from the Aegean to the Black Sea regions allow for a broad spectrum of species, including *Agaricus bisporus* and *Pleurotus ostreatus*, which are widely cultivated[20]. The Black Sea region, with its forested landscapes, is particularly suitable for *Boletus edulis* and *Cantharellus cibarius* [5]. This range of ecological habitats in both countries promotes a variety of mushroom species with significant culinary and economic value.

Climate Influence on Edible Mushroom Biodiversity in Morocco and Türkiye

The climate in Morocco and Türkiye plays a significant role in shaping their respective edible mushroom biodiversity. Morocco experiences a Mediterranean climate along its coast, while inland areas are more arid and semi-arid, particularly in the Sahara and the Middle Atlas regions. These varying conditions restrict the diversity of moisture-loving fungi but encourage desert truffles like *Terfezia sp.*, which are well-suited to arid regions and valued as local delicacies[23, 24]. Mountainous areas in the Rif and Atlas, which have higher precipitation levels, support a limited range of forest-dwelling mushrooms such as *Lactarius* and *Russula* species, though these remain less prominent than in more humid regions globally [25].

Türkiye, with its diverse topography and climates from Mediterranean along the south and west coasts to the temperate and more humid Black Sea region supports a wider range of fungi. The Black Sea's high rainfall fosters species such as *Cantharellus cibarius* (chanterelle) and *Morchella esculenta* (morel), while the Mediterranean regions support *Lactarius deliciosus* and *Boletus edulis*, often integrated into local cuisines due to their abundance [5, 20]. Türkiye's varied climate conditions have thus enabled a greater diversity of both foraged and cultivated mushrooms, supported by different ecosystems in its coastal and mountainous regions [26].

These climate variations make Türkiye more favorable for a diverse fungal ecosystem compared to Morocco. However, Morocco's arid and mountainous regions offer unique species that are highly adapted to local conditions, underscoring the influence of climate on mushroom biodiversity in both countries [27].

Discussion

The edible mushroom biodiversity in Morocco and Türkiye reflects both countries' distinct ecological landscapes and cultural connections to mushroom consumption. In Morocco, mushroom diversity is influenced by Mediterranean and semi-arid climates, leading to unique species like *Terfezia sp.* (desert truffle), highly valued in arid regions, especially in rural areas where it forms a part of local traditions [22, 23]. *Lactarius sanguifluus*, *Boletus edulis*, and *Russula cyanoxantha* are other commonly foraged species in Morocco's mountainous regions such as the Rif and Atlas, though their use remains somewhat limited among the general population due to cultural perceptions and lesser commercial demand [25].

Türkiye, with its more diverse climates spanning coastal and mountainous regions, supports both foraged and cultivated species, making it a larger hub for mushroom consumption and commerce. *Agaricus bisporus* and *Pleurotus ostreatus* dominate Turkish markets as widely cultivated and commercially significant species [5, 20]. The Black Sea and Mediterranean regions of Türkiye are home to wild species like *Cantharellus cibarius* (chanterelle) and *Boletus edulis*, highly prized for their culinary uses and thus contributing to both regional and national markets [28]. This cultivation and foraging pattern provides a greater variety and higher commercial accessibility in Türkiye than in Morocco.

Ecologically, edible mushrooms in both countries play important roles, such as enhancing soil nutrient cycles in forests and forming mycorrhizal relationships. However, while Türkiye has seen a rise in both wild foraging and mushroom farming, Moroccan mushroom use is primarily regional and seasonal, except for cultivated species like *Agaricus bisporus*, which are increasingly found in urban centers [29]. The diversity of species like *Morchella esculenta* (morel) in Türkiye's forested areas, sought after for both culinary and medicinal purposes, highlights the higher commercial viability of Turkish wild mushrooms compared to those in Morocco [26].

Overall, the edible mushroom industries of Morocco and Türkiye differ in scale and cultural integration, with Türkiye's more diversified market benefiting from a greater ecological range and consumer demand. Continued studies on Morocco's underutilized edible mushrooms could reveal new economic potentials, similar to Türkiye's expanded mushroom industry, contributing to biodiversity conservation and rural development in both countries [27]

Conclusion

The biodiversity of edible mushrooms in Morocco and Türkiye highlights how regional climates and ecological factors shape fungal diversity and availability. Morocco, with its predominantly arid and mountainous terrain, hosts unique species such as *Terfezia sp.* that thrive in desert-like conditions, while mountainous regions support a limited but notable range of forest mushrooms. Conversely, Türkiye's varied climates ranging from humid Black Sea forests to Mediterranean and temperate zones foster a broader diversity of both wild and cultivated mushrooms, including species such as *Agaricus bisporus* and *Cantharellus cibarius*. These findings underscore the role of climate in influencing the types and abundance of edible mushrooms across different ecosystems, presenting opportunities for conservation, sustainable harvesting, and potential cultivation in each country. The distinct climatic conditions and resulting mushroom biodiversity enrich local cuisines and traditions, contributing to the ecological and cultural value of these fungi in both Morocco and Türkiye.

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Comparison of Heavy Metal Impacts on Aquatic Biota: Case Studies from Various Geographical

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Abstract

Heavy metal pollution in aquatic ecosystems has become a critical environmental issue caused by human activities, such as industrial waste disposal, domestic activities, and maritime transportation. Heavy metals such as lead (Pb), mercury (Hg), cadmium (Cd), and zinc (Zn) can accumulate in the bodies of aquatic organisms through bioaccumulation and biomagnification processes, which ultimately impact the health of aquatic ecosystems and humans. This study aims to analyze the distribution of heavy metals and their impacts on aquatic ecosystems and identify potential health risks to humans. The method used is a literature study with a narrative approach, where data is collected from scientific literature published between 2019 and 2024. Literature searches were conducted on several academic databases using keywords such as "heavy metals," "aquatic biota," "aquatic ecology," and "pollution." The analysis results show that heavy metals are distributed in water media, sediments, and living organisms with varying concentrations depending on environmental factors, such as pH and redox conditions. The impacts of heavy metals include metabolic disturbances of aquatic microorganisms, decreased biodiversity, and potential hazards to humans through the consumption of contaminated biota. This study also highlights the possible use of aquatic organisms as bioindicators and the development of biota-based bioremediation as a mitigation solution. These findings emphasize the importance of a site-based management approach to address heavy metal pollution and provide a reference for environmental policy and further research.

Keywords: Heavy metal, Aquatic ecosystems, Bioindicators, Health risks.

Discipline: Environmental Science

Introduction

Human activities such as waste disposal, industry, shipping activities and several other activities that cause environmental pollution will decrease water quality and impact the lives of marine biota living in it. Thus, it can cause water pollution, which usually comes from plastic waste, contamination of chemicals and heavy metals that can threaten aquatic biota's lives and disrupt the ecosystem's balance. The population of marine biota that inhabit coastal areas can be used as an indicator of water quality. This is because all of their lives are in the water. Most aquatic biota used as bioindicators can be animals or plants. Animal groups include invertebrates. These animals can be used as bioindicators because they are easy to identify and have different sensitive tolerances to various biotic and abiotic factors in their environment, so the structure of macroinvertebrate communities is generally used as an indicator of the condition of a system. Changes in the presence, number, morphology, physiology and behaviour of organisms can indicate the limitations of the physical and chemical conditions of the environment they prefer [1]. Pollution is a severe problem for human life and all ecosystems, especially in this discussion,

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which is the aquatic ecosystem that includes the biota. Heavy metals are one of the environmental pollutants that can reduce the quality and damage the ecosystem.

Heavy metals are dangerous pollutants because their toxicity, when found in large quantities, can affect the aquatic environment biologically and ecologically [2],[3]. Heavy metals are metals that have a higher specific gravity than light metals. Mercury, lead, cadmium, nickel, manganese, zinc, arsenic and copper are heavy metals. Heavy metal pollution poses a threat to fish and other aquatic life and poses a significant health risk to consumers [4],[5]. Increased levels of heavy metals in seawater will cause heavy metals initially needed for the metabolic process to turn into toxins for marine organisms. This is related to the nature of heavy metals, which are difficult to decompose, so they quickly accumulate in the aquatic environment, and their existence is naturally challenging to decompose [6]. Heavy metals enter the water and accumulate at the bottom of the water. As organisms in the water accumulate them, they will directly affect the lives of organisms exposed to heavy metal pollution. Accumulation through biological processes (Bioaccumulation) will occur through the food chain process so that the accumulation of heavy metals in the body tissue of organisms can occur at every level [7]. Aquatic ecosystems include all living things that exist or live in aquatic environments, such as organisms and their environments that greatly influence each other [8]. According to Utomo [9], aquatic ecosystems can be distinguished based on differences in salinity, such as brackish water, freshwater, and seawater. Fresh water and seawater have relatively different abiotic conditions. According to Muhtadi [8], the abiotic characteristics of freshwater ecosystems are relatively low salinity levels (less than 1%), can be influenced by climate and weather, Relatively low sunlight penetration, and relatively low-temperature variations.

Meanwhile, aquatic ecosystems can be distinguished based on the flow type, namely lotic and lentic waters. Freshwater habitats are divided into two general categories: lentic systems (ponds, lakes, swamps, ponds, reservoirs) and lotic systems (rivers). Lentic systems are waters characterized by stagnant water or no water flow. In contrast, lotic systems are waters characterized by a reasonably strong water flow, classified as flowing waters. A similar thing was stated by Odum [10], who stated that lotic waters are one type of freshwater aquatic ecosystem whose water mass has a current, such as rivers, canals, ditches, and so on. At the same time, lentic waters are freshwater aquatic ecosystems with relatively calm waters, such as lakes, reservoirs, swamps, etc.

After reviewing relevant studies, this study aims to analyze and compare the impacts of heavy metal contamination on aquatic biota from various geographical locations whose data have been collected from previous studies. With a focus on heavy metal accumulation and its implications for aquatic health and ecosystems, this study is expected to provide insight into the variation in the impacts of heavy metals on organisms in different aquatic environments and provide an overview of the potential risks to the food chain and the overall quality of the aquatic environment. This study can also be used as a reference framework to emphasize the importance of an in-depth understanding of the impacts of heavy metal pollution and the need for a site-specific approach in efforts to manage the aquatic environment. This study begins by examining the conditions of heavy metal pollution in aquatic ecosystems in several different environments, such as rivers, lakes, beaches, and lagoon waters, which are affected by industrial activities, shipping, and aquatic environmental conditions. Furthermore, this study explores the concentrations of heavy metals, such as Cd, Pb, Cu, Fe, Mn, Zn, Hg, Al, As, Co, Cr, Mo, and Ni, and their impacts on aquatic biota and human health in various locations including Belawan Port Medan, Cisadane River Estuary Tangerang, Jakarta Bay in Indonesia, Aegean Sea coast in Turkey, Lake Balaton in Hungary, Danube River in Central Europe, Mediterranean coast in Italy, Mississippi River and San Francisco Bay in the United States, Fenghe River and Qinghai-Tibet Plateau in China, Tumkur in India, Red Sea coast in Jeddah Saudi Arabia, Mekong Delta in Vietnam, Lake Victoria in East Africa, and Nile River in Egypt. By identifying local factors that contribute to heavy metal pollution in waters, this study contributes to a more holistic understanding of the challenges. It needs to maintain the sustainability of aquatic ecosystems in various parts of the world."

Distribution and influence of Heavy Metals on aquatic ecosystems

Metals in aquatic systems are part of the water-sediment system, and their distribution is controlled by dynamic equilibrium and physicochemical interactions, which are generally influenced by pH parameters, concentration and type of compounds, reduction-oxidation conditions, and oxidation numbers of the metals [11]. Although it is known that the presence of heavy metals in water is a natural thing that is limited to a certain amount in the water column, sediment, and biota fat, the presence of these heavy metals will increase due to the entry of waste produced by industries and waste from other activities [12]. Types of heavy metals that are classified as having a high level of toxicity include Hg, Cd, Cu, Ag, Ni, Pb, As, Pb, As, Cr, Sn, Zn and Mn [13]. Heavy metals that are moderately toxic consist of the elements Cr, Ni and Co; low toxic consists of the elements Mn and Fe, while highly toxic ones consist of the elements Zn, Hg, Sn, Cd, Pb and Cu [14]. Here are some explanations about the types of heavy metals with high toxicity; the first is zinc, where zinc pollution is a side effect of human activities. Zinc is an essential heavy metal with several functions for biological systems. One case of water pollution by heavy metal waste is zinc (Zn) pollution. Zinc metal in the form of its compounds can enter and pollute the environment [15]. Although the concentration levels are minimal and not found in water, mercury is also a heavy metal toxic to water. Mercury found in waste in public waters is converted by the activity of microorganisms into methyl-mercury (Me-Hg) components, which have strong toxic properties and binding power in addition to their high solubility, especially in the bodies of aquatic animals. This will cause mercury to accumulate either through the process of Bioaccumulation or biomagnification through the food chain in the body tissues of aquatic animals so that mercury levels can reach levels that are dangerous for both the lives of aquatic animals and the health of humans who consume the catch of these aquatic animals [16]; [17]. According to Wulandari [18], Hg is the most dangerous heavy metal among other metals, is cumulative, and can cause death. Tin (Sn) is a metal that is not very toxic; its toxicity will appear when it binds to organic compounds to form organometallics. Organometallics combine organic compounds with inorganic elements (heavy metal Sn); this compound is persistent and toxic to aquatic biota such as molluscs, crustaceans, fish, invertebrates and seagrass communities. Sn metal [19]. Cadmium metal has an oxidation number of +2 and is included in group IIB; ions in solution are colourless, and compounds are not strikingly coloured when in the solid form [20]. Cadmium has an atomic number of 48, an atomic mass of 112.4 and a density of 8.64 g/cm3. The presence of Cd^{2+} ions in water depends on the salt content and acidity (pH). Water with high salt and alkalinity content can accelerate the speciation of Cd^{2+} ions by forming ion pairs [21]. Cadmium metal can enter the water in several ways, namely atmospheric decomposition from industrial activities, soil and rock erosion, rainwater, soil leakage in certain places, and the use of fertilizers in agricultural land [21]. According to Awaliyah [22], the concentration of heavy metals Cu and Pb in water increases as it gets closer to the river mouth. Heavy metals that dissolve in water will be carried to the estuary and accumulate so that the concentration is relatively large because it is easily distributed. The levels of heavy metals from upstream to downstream increase over time, along with the increasing pollutants that enter the river water. This statement is also mentioned by existing research presented by Armid [23], which explains that the concentration of heavy metals in the river's upper reaches is lower due to the large adsorption by suspended solids. Suspended solids will experience adsorption of dissolved heavy metals ranging from 15-83% in freshwater or rivers. Heavy metals dissolved in river water will be adsorbed by fine particles (suspended solids) and then carried by the river flow to the estuary, then settle and undergo a sedimentation process. Three media can be used in the aquatic environment as indicators of heavy metal pollution: water, sediment, and living organisms. Various living organisms inhabit every natural aquatic environment, all of which are part of a trophic system (trophic level) [24]. Heavy metals accumulate in the environment, especially in river and sea sediments, because they can be bound to organic and inorganic compounds through the adsorption process and the formation of complex compounds. After all, heavy metals can accumulate in sediments, so the levels of heavy metals in sediments are greater than the levels of heavy metals in water [25]. Heavy metals in the water will fall and settle on the bottom of the water and then form sediment. This will cause organisms that feed on the bottom of the waters, such as shrimp, crabs and shellfish, to be exposed to heavy metals bound to the bottom of the waters and form sediment [26]. An increase in the concentration of heavy metals that exceeds a certain limit will also affect water quality. Therefore, it is necessary to measure the physical and chemical parameters of the water to see the extent of the quality of the water.

Effects of Heavy Metal Bioaccumulation on Aquatic Biota

Heavy metals such as fish, macroalgae, molluscs, crustaceans, phytoplankton, benthic invertebrates, and amphibians can accumulate in aquatic biota. Heavy metals can accumulate in fish in two ways, namely directly and indirectly; if fish consume contaminated water and food through the digestive system, it is called direct exposure, but if it is through permeable membranes such as skin and gills, it is called indirect. The level of heavy metal concentration in fish indicates the status of heavy metal pollution in the environment. The accumulation of heavy metals in the organs of aquatic organisms can sometimes exceed the heavy metal content in their living environment. Toxic effects usually occur when the concentration of heavy metal absorption exceeds the mechanisms of metabolism, storage, and detoxification [27]. Many marine organisms, such as fish, shrimp, and crabs, are contaminated with heavy metal concentrations from water and sediment [27]. Heavy metals that accumulate in fish can be transferred to humans when contaminated fish are consumed, worsening human health [28].

Furthermore, the existence of organisms that can accumulate heavy metals, namely molluscs, one of which is shellfish because it has low mobility so heavy metals in the soft tissue of its body are considered to represent the presence of heavy metals in its habitat, besides that shellfish are potential biota contaminated with heavy metals due to their filter feeder properties so that shellfish biota are said to be a test in monitoring the level of accumulation of heavy metals, especially lead (Pb) in marine organisms [29]. Crustaceans or shrimp are also one of the biota that have the potential to be affected by heavy metals; this biota is a large group of Arthropods consisting of more than 50,000 species. One example is lobster, crab, and types of shrimp. Examples of species usually cultivated in several areas are tiger shrimp (Panaeus), giant prawns, and crabs. Crustaceans that live in seawater and freshwater always look for food at the bottom of the waters. This is the assumption that several types of crustaceans are exposed to heavy metals and can be used as bioindicators of polluted waters [30], [31], [32]. Shrimp (crustaceans) are invertebrates that feed on the bottom of the water and can accumulate dissolved heavy metals in water [32],[33]. Macro algae also function as biosorbents because they can absorb pollutants in water, one of which is heavy metals. Various species of algae, especially from the green algae group (Chlorophyta), both in living conditions (living cells) and in the form of dead cells (biomass) and immobilized biomass, have received attention for use in absorbing metal ions. Algae in living conditions are used as bioindicators of heavy metal pollution in aquatic environments. Biomass and immobilized biomass biosorbents (biological materials that absorb heavy metals) are used in wastewater management [34]. Plankton are also organisms that can be exposed to heavy metals through Bioaccumulation. Plankton can be divided into two large groups, namely phytoplankton and zooplankton. Phytoplankton and zooplankton live floating following the water current [35]. This condition makes it easy for marine biota to accumulate heavy metals because heavy metals that enter the water cannot be degraded. In this case, phytoplankton have an excellent opportunity to accumulate heavy metals because their surface area is more significant than their volume ratio, so they have a high accumulation capacity in a relatively short time. Heavy metals in the waters enter phytoplankton through the cell membrane and accumulate in the cells. Phytoplankton that have accumulated heavy metals act as the first producers and will be preyed on by zooplankton, which acts as the first consumers, then consumed by larger organisms such as small fish, and then small fish are eaten by larger fish. The discussion on Bioaccumulation is also explained by Bhattacharya [36], who explains that zooplankton, as predators of phytoplankton in the coastal waters of the Indian Sundarban, can be a heavy metal bioconcentration of 4-6 times. This makes heavy metals that accumulate in fish can hurt aquatic organisms. Benthos can also accumulate heavy metals dissolved in water bodies and released from aquatic sediments. The accumulation of heavy metals in the bodies of aquatic animals is influenced by many factors, including the concentration of heavy metals in water and water pH [37].

Ecological Risks and Impacts of Heavy Metal Exposure to Aquatic Ecosystems and Aquatic Organisms

Heavy metals have a considerable atomic weight; another definition of heavy metals is those weighing 5 grams or more per cm". This means 5 times greater than the specific gravity of water, for example, in mercury (Hg), lead (Pb), and cadmium (Cd). Meanwhile, light metals have an atomic weight of less than 5 grams per cm, for example, sodium (Na) and potassium (K). In small amounts, metals are needed by living things for life processes, including for growth and development. In terms of their role in the body of living things, metals are divided into two types: metals that play a fundamental role in the body's metabolic processes, called essential metals and non-essential metals, whose roles have not been widely found in living things. The metal content in the body is minimal, and if it is in excessive amounts, it can cause damage to the organs of the organism concerned [38].

Heavy metals have long been known to harm aquatic organisms and human health. One of the impacts on aquatic organisms is mass fish deaths. Meanwhile, for human health, it is a disruption of metabolism and causes cancer and mutations [39]. The concentration of heavy metals in water can be in water, biota and sediment. However, heavy metals can be in greater quantities in sediments than water bodies due to their ability to bind organic materials [40]. Metals in nature come from various sources, including tectonic processes, volcanic, upwelling, and input from the atmosphere and land. Input from land has the largest role in increasing the concentration of heavy metals in water, one of the consequences of industrial liquid waste. Naturally, metals are already present in seawater, but in tiny amounts, such as research conducted by [41] stating that the content of heavy metals in seawater ranges from 10 to 10 ppm. The concentration of heavy metals in water varies greatly, and one depends on the season; for example, in the rainy season, when rainfall is high, many heavy metals, either in dissolved form or sediment, are carried from land to sea through river flow. Heavy metals can be found in various forms in water, namely dissolved, sediment, or fine grains. Dissolved heavy metals will eventually settle, but this takes a long time. Hutagalung [42] and Rochyatun [43] stated that living organisms need metals for growth and development at low concentrations, but if the levels increase, the metals will become poisonous. There are two mechanisms for heavy metals to enter the body of living things: directly and indirectly. The direct mechanism occurs through the absorption of dissolved heavy metals by organisms that absorb water and nutrients into the body. This mechanism generally applies to aquatic plants such as macroalgae, which absorb nutrients for metabolic processes through osmosis diffusion. Another way heavy metals can enter living organisms' bodies is through the food chain. In the process of eating, materials and energy transfer from the preyed organism to the predator organism. In the composition of the food chain, the beginning of this activity is the plant, which acts as a producer. In the next process, producers will be eaten by consumers at level 1; consumers will eat consumers at level 1 at level 2, and so on. Producers can absorb and accumulate heavy metals in cells. Suppose consumers eat this group of producers at the next comic level. In that case, there will be a transfer of heavy metals into the body of consumers at level 1, and the transfer of heavy metals will continue to the highest trophic level. The higher the trophic level, the greater the accumulation of heavy metals in the body. This is related to the prey biomass and the food chain's length. Aquatic plants or phytoplankton, as primary producers, are not selective in choosing the type of elements they will absorb. Because there is a process of absorption of metal ions, the metal content in the environment, to a certain extent, will be comparable to the metal content in the cells of organisms living in that environment. Based on the results of research conducted by Kelly [44], they compared the accumulation of Zn, Cd, and Pb in several types of freshwater algae and Bryophyta, showing that in the algae Lemanea fluviatilis (Rhodophyta) and Cladophora glomerata (Chlorophyta) there is a positive relationship between the levels of heavy metals in water and in the body of the organism, with the coefficient of determination (RR) for total conditions in water is 0.66 for Lemanea and 0.6'1 for Cladophora except Stigeoclonium tenue, does not show a positive relationship for heavy metals Cd and Pb. It was also added that there are different relationships between species and types of heavy metals. If the amount of toxicant that enters the cell is huge and can no longer be bound to the binding agent, then the toxic properties cannot be neutralized by the cell, resulting in damage to the body system of the organism. The disorders that occur are inhibition of growth and development rates, abnormalities in the form of cells or cell organelles and damage to the function of cell organelles. Another study conducted by Effendi [45] regarding the effect of heavy metals Cd and Cu on Scenedesmus armalus (microalgae) stated that the presence of Cd and Cu in Scenedesmus armatus culture can inhibit the rate of cell photosynthesis and cause changes in the size of the cells. From the explanations above, this study aims to analyze the distribution of heavy metals in aquatic ecosystems based on literature studies, including understanding the physical and chemical factors that influence their distribution in the water column, sediment, and living organisms. In addition, this study evaluates the ecological impact of heavy metals on aquatic biota through direct Bioaccumulation and the food chain by referring to various literature. This study also identifies human health risks from consuming biota contaminated with heavy metals. It provides recommendations for managing aquatic environments, summarized from previous studies. Thus, this literature study is expected to be a reference in understanding the impact of heavy metal pollution and a basis for further research in related fields.

Methodology:

This study uses a literature review/narrative technique to find and analyze relevant research on the Comparison of Heavy Metal Impacts on Aquatic Biota and case Studies from Various Geographical Locations. This study uses the publish or perish application. Then it enters the keywords "Heavy metals", "Aquatic biota", "Aquatic ecology", and "Pollution" using academic databases such as Google Scholar, Research Gate and Web of Science to find relevant publications published in peer-reviewed journals. The search is limited to papers published between 2019 and 2024 to obtain data from the latest research. From the findings, 202 papers with the keywords I have written above.

“Paper screening”, after the search, screening involves the use of inclusion and exclusion criteria. Screening the results to determine which studies are relevant to the research question is very important. This consists of reviewing the "title," "abstract," and "full text" of the study. The criteria included include:

1. Research published between 2019 and 2024

2. Research is in full-text form and published in a well-known digital library/institution.

3. Studies published in peer-reviewed journals.

4. Research related to the research questions that I will conduct

After the relevant studies were identified, 202 papers were found. Then, 16 papers met the criteria mentioned and were used as material for the Comparative Analysis of the Impact of Heavy Metals on Aquatic Biota, Case Studies from Various Geographical Locations. The data will be processed using literature review/narrative analysis, which can become one paper for future research review materials related to relevant topics.

Results

Distribution and Effect of Heavy Metals on Aquatic Ecosystems

Based on the reviewed journals, data were found for the distribution and effect of heavy metals on aquatic ecosystems with the following data:

"Belawan Port", Shows that the highest concentration of heavy metals is lead (Pb), with a value ranging from 15.50 to 68.43 mg/kg, while the heavy metal Hg is below the detection limit in most locations. These metal pollutants are mainly caused by industrial activities, settlements, and port reclamation, which increase concentrations in sediments and waters [46].

"Cisadane River Estuary, Indonesia" The findings identified the concentration of Pb and Zn in estuary waters originating from industrial waste runoff, households, and other human activities along the river. The concentration of Zn ranged from 0.014-0.097 mg/L, with an average of 0.0456 mg/L, while Pb ranged from 0.025-0.051 mg/L [47].

"Aegean Sea, Turkey" The distribution of heavy metals on the Turkish coast, especially in the Aegean Sea, is strongly influenced by anthropogenic activities such as industrial waste discharge, which causes high accumulation of Zn, Cu, and Pb in coastal sediments [48].

"Fenghe River Basin, China" Heavy metals in river water and sediments reach high concentrations, especially in locations with industrial and construction activities. The increase in heavy metals in this area is closely related to urban runoff and agricultural activities. Analysis showed that most heavy metals, especially Mn and Cr, exceeded local environmental quality standards [49].

"Turkish Coast of the Aegean Sea" The distribution of heavy metals along the Turkish coast showed that metals such as Fe, Zn, and Pb accumulated higher in sediments than in seawater. The coast of İzmir Bay showed the highest metal concentrations, with human activities in urban areas contributing to the pollution [50].

"Red Sea, Saudi Arabia" The distribution of heavy metals in the Red Sea showed that anthropogenic activities in the Jeddah coast, such as waste discharge and oil spills, increased heavy metals in sediments. These findings indicate that metals such as Cd and Pb have high bioavailability potential, threatening marine organisms in this area [51].

"Tumkur, India" Research in India shows that surface water and groundwater around the Tumkur area contain different concentrations of heavy metals. Metals such as Cu and Fe are found in high concentrations at several points, especially around locations affected by agricultural and factory runoff [52].

Effects of Heavy Metal Bioaccumulation on Aquatic Biota

Based on the reviewed journals, data was found for the Effects of Heavy Metal Bioaccumulation on Aquatic Biota with the following data:

"Algae in Antarctica" Algae in Antarctica, especially Cladophora glomerata and Lemanea fluviatilis, show high accumulation capabilities of heavy metals such as Cd and Pb. These algae absorb heavy metals from the environment, but excessive accumulation can cause physiological damage to algal cells [53].

"Rome, Italy" A study in an Italian ecosystem showed that mercury (Hg) and cadmium (Cd) biomagnified in the food chain, from phytoplankton to predatory fish. Mercury concentrations were exceptionally high in predatory fish that consume organisms at lower trophic levels, indicating a threat to the ecosystem's health and consumers [54].

"Tumkur, India" The findings identified that heavy metals such as Fe and Cd showed high bioaccumulation potential in fish and other aquatic organisms around Tumkur, India. This bioaccumulation effect caused physiological changes such as metabolic disorders in aquatic biota [55].

"Water Relations in Plants" The study found that heavy metals such as Cd and Zn affected water uptake by plants, especially in roots and leaves, leading to osmotic stress. This suggests that Bioaccumulation of heavy metals can directly impact the physiological processes of aquatic plants and potentially affect the aquatic food chain [56].

"Interactions Between Microplastics and Heavy Metals" The study highlights that microplastics can act as a binding medium for heavy metals in the aquatic environment, which are then absorbed by aquatic organisms. This accumulation shows that microplastics can accelerate the Bioaccumulation of heavy metals in aquatic biota [57]

"Biomagnification Potential" This study shows that biomagnification occurs in heavy metals such as mercury and cadmium at various trophic levels. Heavy metal concentrations from phytoplankton to predatory fish continue to increase, which poses a significant threat to species at higher trophic levels [58].

The Risk and Ecological Impact of Heavy Metal Exposure to Aquatic Ecosystems and Aquatic Organisms

Based on the reviewed journals, data was found for the Risk and Ecological Impact of Heavy Metal Exposure to Aquatic Ecosystems and Aquatic Organisms with the following data:

"Belawan Port, Indonesia" Heavy metals in the waters of Belawan Port significantly impact aquatic organisms such as shellfish, which accumulate in their tissues and threaten human health if consumed. High exposure to Pb metal can disrupt the photosynthesis process in local phytoplankton, reducing ecosystem productivity [46].

"Cisadane River Estuary, Indonesia" High concentrations of Pb and Zn in the Cisadane estuary cause changes in the local ecosystem. These affect the health of fish living in the waters and reduce water quality, which has the potential to negatively impact humans consuming seafood from the area [47].

"Aegean Sea, Turkey" Heavy metal exposure on the coast of Turkey causes increased toxicity in aquatic biota, affecting the food chain and threatening biodiversity. Research shows direct impacts on the physiological functions of organisms at lower trophic levels, especially in predator species [48].

"Rome, Italy" Mercury and cadmium biomagnification in Italian marine ecosystems threatens top predators, both animals and humans. Concentrating these metals in predatory fish increases the risk of toxicity to end consumers in the food chain, causing severe health impacts [54].

"Heavy Metal Pollution in Aquatic Environment" Exposure to heavy metals in water affects various physiological aspects of aquatic organisms. Findings indicate that metals such as Pb and Cd can disrupt the function of aquatic organisms' organs, leading to a decrease in biodiversity in contaminated areas [59].

"Biomagnification in Aquatic Ecosystems" This study confirms that heavy metals such as Hg and Cd have a high potential for biomagnification in aquatic ecosystems. Toxic effects at higher trophic levels can change the structure of biota communities and decrease ecosystem stability [58].

"Turkish Coast of the Aegean Sea" This study shows that high concentrations of heavy metals along the Aegean coast affect algae as bioindicators and threaten other organisms in the aquatic food chain, increasing the overall risk of toxicity [50].

"Red Sea, Saudi Arabia" In the Red Sea, high concentrations of heavy metals due to industrial waste discharges increase the risk of toxicity in coastal ecosystems, which impacts the health of biota and the ecological balance in the area [51].

Opportunities

Utilization of Aquatic Biota as Bioindicators

A number of studies in this journal show that algae and shellfish species can absorb significant amounts of heavy metals. Lemanea fluviatilis and Cladophora glomerata in Antarctica, for example, show potential in absorbing Cd and Pb metals. This opens up opportunities to use these biota as bioindicators in water quality monitoring. The ability of certain biota to act as heavy metal accumulators can be utilized in efficient monitoring and assessment methods for the impact of metal pollution in aquatic ecosystems [46].

Development of Biology-Based Remediation Technology

Heavy metals accumulated in macroalgae and aquatic plant tissues indicate that specific aquatic biota have the potential to be natural phytoremediation agents. Some algae species can absorb and store heavy metals, making them natural agents that reduce heavy metal concentrations in aquatic environments. The use of plant and microorganism-based biotechnology for heavy metal remediation has the potential to be a more environmentally friendly method compared to conventional chemical approaches [46], [47]

Opportunities for Environmental Policy and Regulation Development

This study also opens up opportunities for developing stricter and more targeted policies in industrial waste management. Several studies conducted in coastal areas of Turkey and Italy indicate that human activities directly contribute to heavy metal pollution. With this empirical evidence, governments and policymakers can build better regulations in controlling waste disposal and tighten environmental monitoring in order to prevent more serious heavy metal pollution in the future [46]

Challenges

Bioaccumulation and Biomagnification in the Food Chain

One of the biggest challenges identified by these journals is the phenomenon of heavy metal biomagnification, such as Hg and Cd, which threaten organisms at high trophic levels. These heavy metals accumulate through the food chain, from phytoplankton to predatory fish, increasing the risk of toxicity to animals and humans that consume them. Overcoming this challenge requires long-term monitoring and a holistic approach that includes the entire food chain, which may require significant costs and resources [59]

Diversity of Biota Responses to Heavy Metal Exposure

Each species of aquatic biota shows different levels of sensitivity to heavy metals, which makes generalization of toxicological impacts difficult. Certain species may be more tolerant to heavy metal exposure than others. This poses a challenge in designing effective remediation or mitigation strategies for the entire ecosystem, as they need to be tailored to the specific characteristics of each biota and its habitat [47]

Limitations of Effective and Economic Environmental Recovery Technologies

Although recovery technologies such as phytoremediation have great potential, their application is still limited to certain types and concentrations of metals. Some heavy metals, such as Hg, are persistent and difficult to remove with biological techniques. In addition, this technology often takes a long time, and the results can vary depending on environmental conditions. Finding an effective, fast, and economical method for the restoration of aquatic environments contaminated with heavy metals is a challenge [46],[47].

The Role of Microplastics as Heavy Metal Transport Media

In several studies, such as on microplastics in the Aegean and Red Sea waters, microplastics were found to bind heavy metals, increasing the distribution and transport of heavy metals in aquatic ecosystems. The interaction between microplastics and heavy metals adds to the challenges in pollution management because microplastics not only affect local waters but can also spread to broader areas, increasing the risk of metal bioaccumulation on a broader scale [48]

Conclusion

The distribution of heavy metals in aquatic ecosystems is greatly influenced by human activities, such as industry and domestic waste, which contribute to high concentrations of heavy metals in sediments. Bioaccumulation of heavy metals in aquatic biota threatens ecosystem health, where metals such as Pb, Cd, and Hg accumulate at higher trophic levels through biomagnification. The ecological effects of heavy metal exposure include decreased biodiversity, impaired metabolic function of aquatic organisms, and health risks to humans who consume polluted biota. Opportunities to utilize aquatic biota as bioindicators and remediation agents provide hope for mitigating the impacts of heavy metals. However, challenges such as biomagnification, variations in biota responses, technological limitations, and interactions with microplastics must be addressed comprehensively. A combination of strict environmental regulations, the development of efficient recovery technologies, and continuous monitoring can help reduce the impacts of heavy metals on aquatic biota and support the sustainability of aquatic ecosystems.

Recommendations

1. Waste Management and Monitoring—The control of industrial and domestic waste needs to be tightened to prevent the increase in heavy metals in waters.

2. Routine Ecosystem Monitoring – Regular monitoring of water and sediment quality should be carried out to detect increasing pollution and its impacts on aquatic ecosystems.

3. Ecosystem Remediation – Further research is needed to develop remediation methods, such as phytoremediation, to efficiently reduce heavy metals in water.

These efforts are expected to protect aquatic ecosystems from heavy metals' negative impacts and maintain the health of aquatic biota and humans.

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Evaluation of biological activities of *Melia azedarach* species and its importance in phytotherapy

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Abstract

Medicinal plants have been widely recognized and used across different civilizations due to their therapeutic properties, which has led to increased interest from researchers in herbal products because of their availability, efficacy, and lower side effects. However, the search for more effective and safer natural therapeutic sources remains a continuous challenge in the field of medicine, as the need grows to discover new plant compounds that exhibit strong therapeutic properties with lower side effects. This study aims to investigate *Melia azedarach*, commonly known as the Chinaberry tree from the Meliaceae family, and to explore its therapeutic efficacy through the analysis of its active chemical components and associated biological activities. A systematic review of the literature was conducted, analyzing 350 scientific publications, with 55 studies selected based on specific quality criteria, such as a focus on biochemical analysis and biological activities. The results revealed that *Melia azedarach* contains compounds such as alkaloids, flavonoids, and phenolic compounds, which exhibited antimicrobial, antioxidant, anti-inflammatory, anthelmintic, and antitumor properties. This study contributes to enhancing scientific understanding of *Melia azedarach* potential as a natural therapeutic agent and highlights the need for further future research to understand the mechanisms of action of these compounds and develop effective plant-based medicines for treating and managing various disorders.

Keywords: Medicinal plants, *Melia azedarach*, biological activities, phytochemical composition, phytotherapy.

Introduction

Phytotherapy, derived from the Greek term meaning "plant treatment," refers to the use of plants and their extracts for therapeutic purposes [1]. The modern concept of phytotherapy was developed by French physician Henri Leclerc, who coined the term in 1913 and played a pivotal role in establishing its use in medical practice. Since then, medicinal plants have continued to serve as an integral part of global healthcare systems [2]. More than 3.3 billion people in developing countries rely on these plants for treatment, and the World Health Organization (WHO) estimates that around 80% of individuals in underdeveloped nations rely on traditional medicine for their primary healthcare needs. In recognition of this, the WHO has developed strategies, guidelines, and standards to regulate the use of herbal medicines [3]. Medicinal plants are not only important in traditional medicine but also serve as valuable sources of active compounds for the development of modern pharmaceuticals [4]. Among these plants, *Melia azedarach*, a member of the Meliaceae family, holds significant importance in phytotherapy. Commonly referred to as Chinaberry, Umbrella Tree, Shade Tree, or Persian Lilac, Worldwide distributed in tropical and subtropical regions, native to Southeast Asia (especially India, Pakistan and China). It was introduced and naturalized in Africa, Australia, Europe, and the Americas this is due to its adaptability to different climates [5]. *Melia azedarach* comprises around 50 genera and over 550 species; this plant can grow up to 15 meters tall and is known for its large, compound leaves. In summer, it blooms with flowers arranged in clusters, which later develop into yellow, bead-like fruits for this

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reason, it is called “tesbih tree" in Turkish [6]. Traditionally, *Melia azedarach* has been used in Ayurveda, Siddha, and Greek medical systems for its various therapeutic properties, including as an anthelmintic, diuretic, emmenagogue, expectorant, and vermifuge, as well as in the treatment of hysteria, and leprosy [7]. Recent research has confirmed the plant’s medicinal potential, showing it possesses a range of biological activities, such as antifungal, anti-malarial, antibacterial, hepatoprotective, antioxidant, anthelmintic, antipyretic, and cytotoxic effects. Furthermore, *Melia azedarach* extracts have shown insecticidal activity and therefore, it can be used as an alternative to synthetic chemical pesticides, possessing insecticidal and ant parasitic properties that can help control pests and parasites in a more environmentally friendly manner. These properties are attributed to the phytochemicals, which includes alkaloids, flavonoids, phenolic acids, terpenoids, saponins, glycosides, and coumarins [7].

Materials and Methods

A comprehensive literature review was conducted to gather studies on the biological activities of *Melia azedarach* and its role in phytotherapy. Databases such as PubMed, Science Direct, and Google Scholar were searched using relevant keywords. Articles published in English, without date restrictions, were included. Studies were selected based on predefined criteria, focusing on *Melia azedarach* pharmacological properties, mechanisms of action, and therapeutic uses. Irrelevant studies were excluded, and the quality of the selected research was thoroughly evaluated for credibility and relevance.

Traditional uses of *Melia azedarach*

Melia azedarach has a rich history of traditional uses across different cultures. Table 1 provides a comprehensive overview of the various traditional applications associated with *M. azedarach*, plant part used and method of application

Table1: Traditional uses of Melia azedarach

Plant part	Traditional uses	Method of application
Leaves	Diuretic, anthelmintic, effective in skin diseases like leprosy, chicken pox, smallpox, hysteria. Toothache, headache, fever, rheumatic pain, malaria, gingivitis, piles, pyrexia and insecticide [5].	Externally for burns. Internally and externally in skin diseases. Used externally like compresses to alleviate both headaches and fever. Mouth wash in gingivitis and toothache. Internally in anthelmintic, diuretic, and expectorant.
Stems	Spleen enlargement, asthma, general debility, antispasmodic, antiviral, gonorrhea, tiredness, cough and loss of appetite [5].	Internally
Fruits	For the treatment of diabetes, purgative, emollient, antihemorrhodial, killing lice and anthelmintic [8].	Internally

Flowers	Bacterial skin diseases, astringent, diuretic, anthelmintic, cough and anodyne [7].	Internally and externally
Seeds	Malaria fever, leprosy, scrofula, helminthiasis, rheumatism and in pelvic region pain [9].	Internally and externally
Roots	Astringent, anodyne, antiseptic, anthelmintic, constipating, expectorant, febrifuge, cough, asthma lumbago, leprosy, dysmenorrhea, diabetes and abnormal urethral discharge [9].	Internally and externally
Barks	Antidiarrhoeal, diuretic, rheumatic pain, fever, overall debilitation, stomach upset and gonorrhea [10].	Internally

Phytochemical Constituents

The chemical composition of *Melia azedarach* is highly complex. The different parts of *Melia.azedarach* have been shown the presence of various phytochemicals groups which include flavonoids, alkaloids, terpenoids, saponins, steroids, tannins, limonoids, coumarins and anthraquinones which exhibit different pharmacological activities.

Roots contain limonoids and coumarins like 1-Tigloyl-3,20-diacdyl-11-methoxyrneliacarpinin, 1-Deoxy-3- methacrylyl-11 methoxyameliacarpinin, l-Cinnamoyl-3-hydroxy-11 methoxyameliacarpinin, meliacarpinin E. Terpenoids like salannal, trichilin-B and trichilin H . The roots also contain flavonoids such as apigenin, β-sitosterol and phenolic acids such asvanillic acid and trans-cinnamic acid derivatives of benzoic acid, which mainly serve as antioxidant activity of the plant [11].

Leaves contain terpenes such as α, β- Pinene, α-Terpineol. Phenolic compounds such as kaempferol, quercitrin and rutin. Limonoids are found in the leaves, such as l-Cinnamoyl 3-acetyl-11-hydroxy Meliacarpin, l-Cinnamoyl-3-methacrylate-l1-hydroxy meliacarpin, Deacetylsalannin, 1,3- dicinnamoyl-l1-hydroxyrneliacarpin [12].

Stem bark contain terpenes such as 3ahydroxyeupha-7,24-diene-21,16-olide, pyroangolensolide. Coumarins such as fraxinellone. Glycosides such as 3-O-α-L-rhamnopyranosids and 7-α-acetoxy-14β-15β-epxygedunan-1-en-3-0-β-D-glucopyranosids. Anthraquinones like 1,3,5,8-Tetrahydroxy-2-methyl anthraquinone and 1,5-dihydroxy-8-methoxy-2-methylanthraside. Alkaloids like 4-methoxy-1-vinyl-beta-carboline and 4, 8-dimethoxy-1-vinyl-beta-carboline [12].

Fruits contain limonoids such as meliacins, sendanin, sendenal, melianone, nimbolidins A and B. also contain polyketides, terpenoids and fatty acids like stearic acid and octadecanoic acids [12].

Seeds contain coumarins such as meliacarpin. Limonoids such as meliacarpin and 1,12-diacetyl trichilin-B. Terpenoids such as meliartenin, melianolmeliacin and tingenone. Fatty acids such as oleic acids, linoleic acids, linolenic acids. Sterols such as daucosterol, stigmasterol, β-sitosterol. It also contains amino acids [11].

Pharmacological activities

Antibacterial and antifungal activities

A study was published in 2016 by Nazar et al. on the antibacterial activity of *Melia azedarach* fruits against *Bacillus subtilis, Proteus, Pseudomonas aeruginosa, E. coli, Staphylococcus aureusand* and *Klebsiella.* The results showed that both aqueous and alcohol extracts of *Melia azedarach* fruit exhibited significant antibacterial activity against the tested bacteria [13].

A study was published in 2012 by Mohamad amin et al. On the antibacterial activity of seeds, fruits, leaves, and flowers of *Melia azedarach* against *Xanthomonas campestris pv. Campestris*, *Pseudomonas syringae pv. Syringae* and *Rathayibacter tritici*. That destroys agriculture crops. The results showed that parts of the plant that were extracted by methanol have an antibacterial effect against both gram-positive and gram-negative plant pathogens [14].

A study was published in 2019 by Kathireshan et al. On the antibacterial activity of *Melia azedarach* leaves extracted by ethanol, methanol, and acetone against various pathogenic bacteria and fungi. The results showed that the ethanol extract is more effective compared to other extract. Furthermore, the ethanol extract show its effectiveness against both *Aspergillus niger* and *Candida albicans* compared to other extract [15].

A study was published in 2011 by Abdul Viqar et al. on the antibacterial activity of *Melia azedarach* seeds extracted by aqueous, methanol, ethyl acetate, benzene and petrol solvents at different concentrations against 18 types of gram-positive and gram negative bacteria isolated from hospital that cause human pathogenic. The results showed that the extract from ethyl acetate showed the greatest amount of inhibition compared all the extracts against all tested pathogens [16].

Antiviral activity

A study was published in 2009 by Erina et al. on the antiviral activity of meliacine compound, derived from *Melia azedarach* leaves in a mouse model of genital herpes infection were examined. The results showed that the severity of sickness was attenuated in the treated mice, accompanied by reduced virus shedding in vaginal fluids. Moreover, Meliacine administration resulted in increased levels of Interferon-gamma (IFN-γ) and Tumor necrosis factor alpha (TNF-α) in the vaginal secretions compared to the infected mice that did not receive treatment. Additionally, the quantity of virus that migrated to the brain was reduced in the Meliacine-treated group. These findings suggest that meliacine may hold promise as a potential alternative therapeutic agent for managing HSV-2 genital infection [17].

A study was published in 2023 by Bahaa et al. on the antiviral activity of *Azadirachta indica* and *Melia azedarach* leaves extracted with methanol on the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) is a strain of coronavirus that causes COVID-19 (coronavirus disease 2019) in vitro. The results showed that both extracts inhibit replication of SARS-CoV-2 virus in vitro at IC50 concentrations 8.451µg/mL for *Azadirachta indica* and 6.922 µg/mL for *Melia azedarach* [18].

Antileishmanial activity

A study was published in 2014 by Imran khan et al. on the antileishmanial effect of *Melia azedarach* was evaluated using green fruit extract and ripe fruit extract. The study focused on *Leishmania tropica* and employed an in vitro promastigote assay, with Amphotericin B used as the reference drug. The results showed that the green fruits had high activity against Leishmaniasis compared to ripe fruits. The enhanced activity observed in the green fruits may be because to highe levels of lemonoids and azadirachtin [19].

A study was published in 2011 by Kawther et al. on the antileishmanial effect of ripe fruit *Melia azedarach*. The study focused on *Leishmania donovani* and employed an in vitro Promastigote assay to assess the leishmanicidal activity of *Melia azedarach* fruits on various biochemical parameters in the liver of mice infected. Results demonstrate that the extract of *Melia azedarach* has potential leishmanicidal capabilities, effectively suppressing the growth of parasites in laboratory mice [20].

Antimalarial activity

According to a study by Charturvedi et al. in 2006, the antimalarial activity of methanol extracts of leaves, bark, and fruits of *Melia azedarach* was assessed using experimental mice infected with the malaria parasite *Plasmodium berghei*. The study utilized Chloroquine as a reference drug for comparative analysis. The results of the study demonstrated that the extracts derived from the fruits and bark exhibited substantial reduction in parasitemia during the early stages of infection. Although the leaf extract also displayed a suppressive effect, it did not reach statistical significance. In the chronic phase of the infection, both the fruit and bark extracts exhibited notable suppressive effects after 5 days of administration. By day 9, these extracts showed significant reduction in parasitemia, albeit to a lesser extent compared to Chloroquine [21].

According to a study by Selvaraj et al. in 2011, the antimalarial activity of leaf extract and fruit extract of *Melia azedarach* was assessed against different species of malarial vectors, including Aedes aegypti, Anopheles stephensi, and Culex quinquefasciatus, under laboratory conditions. The results demonstrated that both the fruit and leaf extracts of *Melia azedarach* exhibited potent larvicidal activity against the mosquito species known to be malarial vectors [22].

Anti-inflammatory activity

In a study conducted by Akacha et al. (2016), the anti-inflammatory activities of the ethanolic leaf extract of *Melia azedarach* were investigated using the carrageenan-induced hind paw edema model in rats, with indomethacin used as the standard drug for comparison. The results of the study demonstrated that the ethanolic leaf extract of *Melia azedarach* exhibited significant inhibition of carrageenan-induced paw edema, comparable to the effects of indomethacin. The extract, administered at a dose of 150 mg/kg, displayed the highest anti-inflammatory activity, reducing paw edema by approximately 25% after 2 hours of treatment. In comparison, indomethacin at a dose of 10 mg/kg showed a reduction of around 32% [23].

In a study published by Gagan et al. in 2015, the anti-inflammatory activity of *Melia azedarach* seeds was evaluated using carrageenan-induced paw edema and formalin-induced inflammation tests conducted on Wistar rats. Indomethacin was used as a reference drug for comparison.

The results of the study demonstrated that the hexane extract of *Melia azedarach* seeds exhibited significant reduction in carrageenan-induced paw edema in comparison, the standard drug Indomethacin. Additionally, in the formalin-induced paw edema model, the seed extract displayed a reduction in inflammation depend on dose [24].

In a study published in 2010 by Vishnukanta et al. , the anti-inflammatory activity of *Melia azedarach* roots was evaluated using the carrageenan-induced paw edema test conducted on Swiss albino mice. The ethanolic extract of *Melia azedarach* roots was orally administered to the mice. The findings revealed that the ethanol extract of *Melia azedarach* roots exhibited a significant reduction in carrageenan-induced paw edema [25].

In a study published in 2012 by Singh P et al., the anti-inflammatory activity *M. azedarach* bark was investigated by carrageenan-induced paw edema model in rats. The ethanol bark extract was orally administered to the rats at doses of 200 and 400 mg/kg body weight, and the paw volume was measured at various time intervals. The results of the study demonstrated that the ethanol bark extract significantly reduced paw edema induced by carrageenan in a dose-dependent manner. The highest level of inhibition at the dose of 400 mg/kg [26].

Antioxidant activity

According to a study in 2012 by Mohammed Fazil et al. , to assess antioxidant activity of *Melia azedarach* leaves extracted with distilled water, ethanol and petroleum ether. the antioxidant activity was evaluated by using the 2,2-diphenyl-2-picrylhydrazyl (DPPH) radical scavenging assay. The findings of the study demonstrated that the ethanol extract of *Melia azedarach* has the most potent radical scavenging activity, after that aqueous extract, and the petroleum ether extract. This antioxidant activity of *Melia azedarach* is ascribed to flavonoids and phenolic compounds [27].

In a study published by Adil Munir et al. in 2012, the antioxidant effect of bark, stem, leaves and fruit sun-dried and air-dried extracts from different parts of *Melia azedarach* was assessed using various in vitro antioxidant assays, including DPPH free radical scavenging activity, Total Flavonoid Contents (TFC), Total Phenolic Contents (TPC), and the percentage inhibition of linoleic acid oxidation. All experiments showed that the stem bark of *Melia azedarach* had the highest antioxidant activity, with sun-dried samples showing more antioxidant activity than air-dried extracts [28].

In a study published by Imran Khan et al. in 2014, to assess antioxidant activity of *Melia azedarach* extracts obtained from green and ripe fruits by using the 2,2-diphenyl-2-picrylhydrazyl (DPPH) radical scavenging assay. The results revealed that the green fruit extract exhibited a maximum antioxidant activity at the highest concentration of 100 µg/mL, whereas the ripe fruit extract showed a lower antioxidant activity at the same concentration. These results indicated that the antioxidant activity of the plant extract was dose-dependent. Furthermore, the study found that the green fruits contained a higher amount of phenolic compounds, resulting in greater antioxidant activity [19].

In a study published by Gayatri Nahak et al. in 2010, to assess antioxidant activity of leaves from *Azadirachta indica* and *Melia azedarach* by using the (DPPH) radical scavenging assay. The results revealed that the extracts of *Azadirachta indica* had highest antioxidant activity compared to *melia azedarach* [29].

In a study published by Khatoon et al. in 2014, to assess antioxidant activity of *Melia azedarach* bark extracted by n-hexane and methanol by using the 2,2-diphenyl-2-picrylhydrazyl (DPPH) radical scavenging assay. The results demonstrated that the n-hexane extract of *Melia azedarach* exhibited higher antioxidant activity compared to the methanolic extract [30].

Wound healing activity

In a study published in 2012, Vidya et al. conducted an investigation to assess the wound healing properties of *Melia azedarach* leaf extract in alloxan-induced diabetic rats. The evaluation of wound healing efficacy was performed using an excision wound model, with povidone iodine ointment serving as the reference standard. The study measured and analyzed wound contraction and the percentage of wound contraction for a duration of 18 days. The findings demonstrated that the topical application of methanolic *Melia azedarach* leaf extract promoted wound healing in diabetic rats, with a comparable effect to the standard povidone iodine. The enhanced wound healing observed in diabetic rats could be attributed to the antimicrobial activity of the Melia azedarach leaf extract [31].

In a study published in 2015, Kumar et al. conducted research to assess the wound healing properties of Melia azedarach leaf ethanolic extract in rats. The study utilized both the excision and incision wound healing models, with povidone-iodine serving as the standard drug. The findings revealed that the topical application of ethanolic Melia azedarach leaf extract at different concentrations exhibited a significant effect in reducing the wound area. The wound healing activity of the extract was found to be significantly higher compared to the standard treatment [32].

In a study published in 2015, Al-Khafaji et al. conducted a performance evaluation of *Melia azedarach* fruit ointment in the surgical wound healing process in donkeys, comparing it to natural wound healing without any medication. The findings demonstrated that *Melia azedarach* fruits proved effective in treating infected wounds this activity attributed to anti-inflammatory and antibacterial activities [33].

Analgesic and antipyretic activities

In a study published in 2013, Sultana et al. conducted research to assess the antipyretic effect of *Melia azedarach* leaves using the yeast-induced pyrexia method in rabbits. The results indicated that hydro-methanol extract of *M. azedarach* leaves, at a dose of 500 mg/kg, possesses a significant antipyretic effect against yeast-induced elevated temperature [34].

In a study published in 2013, Asadujjaman et al. conducted research to assess the analgesic effect of *Melia azedarach* leaves using the acetic acid-induced writhing test in mice. The findings demonstrated that the extract of *Melia azedarach* leaves exhibited dose-dependent writhing inhibition [35].

Anthelmintic activity

The anthelmintic efficacy of fruit extracts from *Melia azedarach* plants was examined in a study by Szewczuk et al. published in 2006. The extracts were tested against the hookworm "*Bunostomum trigonocephalum*", the nodular worm "*Oesophagostomum columbianum*", the tapeworm "*Taenia solium*", and the earthworm "*Pheretima posthuma*". Hexylresorcinol and piperazine phosphate were utilized as standared drug. The results indicated that *Melia azedarach* fruit exhibited higher activity against hookworms and tapeworms compared to piperazine phosphate and hexylresorcinol, respectively. However, the lethal effect on nodular worms was lower than that of hexylresorcinol. The mean time of death values for the drupe extract of *Melia azedarach* against tapeworms were superior to those observed for hexylresorcinol [36].

In a study conducted by Cala et al. in 2012, the in vitro anthelmintic effects of fruit extracts obtained from *Melia azedarach* were evaluated against sheep gastrointestinal nematodes using the egg hatch test (EHT) and larval development test (LDT). The fruit extract exhibited anthelmintic activity [37].

In a previous study, Gajmer et al. (2002) conducted research to evaluate the anthelmintic activity of *Azadirachta indica* and *Melia azedarach* seeds collected from India and extracted by methanol. Seed extracts were examined on the oviposition and egg hatching of Earias vittella, an Asian "spotted bollworm" known for attacking the fruiting bodies of certain crops, particularly cotton. The results of the study indicated that the methanolic extracts obtained from *Azadirachta indica* and *Melia azedarach* showed adverse effects on the egg-laying behavior, fecundity, and hatching of E. vittella eggs. [38].

Anticancer activity

In a study published in 2013, Jafari et al. conducted research to evaluate the anticancer properties of *Melia azedarach* leaves, seeds, and fruits extracts on HT-29", "A-549", "MCF-7", "HepG-2", and "MDBK" cell lines. The results indicated that *Melia azedarach* seed extract exhibited the highest level of cytotoxicity and selectivity against these cancer cell lines, with an IC_{50} range of 8.18–60.10 µg/mL. On the other hand, *M. azedarach* leaf methanol extract showed a relatively lower cytotoxic effect [39].

In a study published in 2020, by Nerome et al. conducted an investigation to evaluate the anticancer effects of *Melia azedarach* aqueous leaf extracts againts HT-29 colon", "A549 lung", and "MKN1 gastric cancer cell lines. The results revealed that the extracts of *M. azedarach* exhibited potent antiproliferative activity against HT-29, A549, and MKN1 cancer cell lines in the colon, lung, and stomach, respectively. Furthermore, in mice with transplanted MKN1 gastric cancer xenografts, significant growth inhibition was observed upon treatment with *Melia azedarach* leaf extracts. Similarly, in veterinary hospitals, dogs suffering from different malignancies showed an average recovery rate of 76% when administered *Melia azedarach* leaf extracts. This study also identified that the *Melia azedarach* leaf extract acts as an autophagy-inducing agent and stimulates the production of Tumor Necrosis Factor-alpha (TNF-α), which may play a role in inhibiting in vivo tumor growth [40].

In a study published in 2023, by Satia et al. conducted research to assess the anticancer effect of *M. azedarach* methanolic leaf extract against LNCaP, MDAMB-231, and MCF-7 cancer cell lines. The results revealed that the extract exhibited low to moderate anticancer activity against LNCaP, MDA-MB-231, and MCF-7 cell lines. In this study anticancer activity of *M. azedarach* attributed to kaempferol 7-O-rutinoside 1 and 4-methoxyresorcinol [41].

Toxicity

To assess the toxicity of *Melia azedarach* flowers and berries, experiments were performed on rats and mice using both water and alcohol extracts. The administration routes included oral ingestion and intravenous injection. The findings revealed that the water and alcohol extracts exhibited no toxicity up to a dose of 1500 mg/kilogram when administered orally to mice and rats. Intravenous injection of the aqueous extract resulted in LD_{50} values of 395 mg/kg in mice and 500 mg/kilogram in rats for flowers, while berries showed LD_{50} values of 700 mg/kg in mice and 925 mg/kg in rats [42]. Another study to determine LD_{50} orally and intraperitoneally of *Melia azedarach* fruit extracts on rats. The result was that oral administration of a maximum of 16 g/kg of extract did not cause major behavioral changes, morbidity or mortality in rat. Nevertheless, the intra-peritoneal LD_{50} was 1.03 g/kg. The lung was the directly impacted organ in the intraperitoneal research according to histopathology, which also revealed muscle disintegration, a significant inflammatory infiltration surrounding the bronchi and bronchioles, and an increase in the mucous production of the epithelial cells that line the bronchi [43]. Toxicity not depends only on dose but also on the part plant used and route of administration. A higher extract concentration significantly slows down breathing [43].

Conclusion

Melia azedarach plant is a rich source of primary and secondary metabolites with significant pharmaceutical and medicinal value in phytotherapy. Studies highlighted its antioxidant, anti-inflammatory, anticancer, antibacterial, antifungal, antiviral, analgesic, and antipyretic properties and phytochemical composition. This review of the literature confirms the therapeutic potential of various parts of *Melia azedarach* in herbal medicine. By understanding its biological activities and phytochemical composition, this current study may help researchers develop herball medicines for the treatment and management of various disorders. However, additional investigation is required to clarify the exact mechanisms through which it operates, identify the active compounds responsible for these activities, and evaluate their safety and efficacy in clinical settings. The evidence gathered so far shows through these studies that *Melia azedarach* is an important resource in phytotherapy, encouraging more research into its healing potential.

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Sustainable Water Remediation Using Plant-Based Nanoparticles with Their Photocatalytic Activity

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Abstract

The need for creative and long-lasting restoration methods is driven by the growing problem of water contamination. Water treatment has shown to benefit greatly from nanotechnology, especially when it comes to the application of nanoparticles (NPs). The present review is focused on the green production of nanoparticles derived from plants and their potential for effective water remediation through photocatalysis. Utilizing natural extracts, plant-based green synthesis minimizes environmental effect and provides a greener alternative to traditional chemical techniques by lowering the use of hazardous chemicals. Additionally, the concepts and procedures pertaining to the environmentally friendly synthesis of plant-based nanoparticles will be examined, along with the potential for photocatalytic material optimization of these biogenic materials. With regard to the increasingly acknowledged serious risks to water quality, we specifically look at their function in the breakdown of organic pollutants, the elimination of inorganic contaminants, and the treatment of new contaminants. The methodology analyzes literature on nanoparticles, their photocatalytic mechanisms, and applications in degrading dyes, pesticides, pharmaceuticals, and heavy metals. It evaluates efficiency under various environmental conditions, highlighting green synthesis principles, photocatalytic efficiency factors, and their integration into water treatment systems. By addressing the promise and shortcomings of plant-based nanoparticles in these crucial areas of water remediation, this review intends to direct future research and development efforts toward more sustainable and effective solutions to worldwide water pollution.

Keywords: Water remediation, Green nanotechnology, Photocatalysis, Plant-based nanoparticles
Discipline: Science and Engineering, Biology

Introduction

Water scarcity is one of the most significant global problems, and it is exacerbated by population growth and urbanization. When various pollutants infiltrate water supplies, there are serious health concerns to the general public. Therefore, there is an urgent need to develop advanced technologies that can detoxify and clean water. These water filtering technologies are crucial for enabling demand-driven water recycling in addition to protecting public health (Rathod et al., 2024).

Effective remediation strategies are necessary to restore water quality and ensure safe drinking water. Biological remediation approaches, like phytoremediation and microbial degradation, have gained popularity for detoxifying contaminated water due to their sustainability and effectiveness (Hellal et al., 2024). A variety of methods, including nanotechnology, have been used for wastewater treatment. The use of nano-photocatalytic technology to combat water pollution has drawn a lot of interest (Ishfaq et

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al., 2023). Although there are still concerns about long-term environmental effects, advances in nanotechnology provide creative approaches to increase water treatment efficacy (Rathod et al., 2024).

Nanotechnology has applications in practically every branch of science and technology. At the same time, it contributes in the identification of solutions to a variety of environmental issues, particularly water contamination. Nanomaterials have several benefits over traditional materials, including both polar and non-polar chemistries, controllable and size-tunable properties, and easier biodegradation, making them great candidates for water and environmental remediation as well (Baby et al., 2022; K. K. Singh, 2022).

Numerous investigations have documented nanoparticles larger than 100 nm, despite the fact that nanoparticles are generally described as having dimensions between 1 and 100 nm. Acknowledging that size alone does not entirely govern nanoparticle behavior or functioning, this broad range represents the diversity in nanoparticle production and application (Saleem & Zaidi, 2020). NPs have significant advantages in wastewater treatment due to their enormous surface area and catalytic, optical, electronic, magnetic, hydrophilic, hydrophobic, and antibacterial capabilities (Roco et al., 2011; Goyal, 2017; Trivedi & Bergi, 2021). NMs are added to the membrane to improve the efficiency of water treatment procedures. NPs can respond to membrane stimuli such as pH and temperature (Baig et al., 2021). Due to the fact that nanoparticles released into the environment without precautions can cause toxicity and environmental degradation, bio-based nanoparticles, which are affordable, biocompatible, and biodegradable, are attractive for wastewater treatment and water purification, improving the sustainability and effectiveness of water pollution removal (Saud et al., 2024). In addition, The increasing demand for nanoparticles and nano-based products raises concerns due to high investment and toxic agents in chemical and physical methods. Green chemistry offers a solution to these issues, addressing the environmental and living entity risks associated with traditional synthesis methods (Niveditha et al., 2024; Garg et al., 2024).

Green nanotechnology is a rapidly developing field that aims to enhance health and environmental applications by creating nanoparticles from live cells via biological pathways (Vijayaram et al., 2024). Specifically, there are two approaches for synthesizing NPs: "bottom-up" and "top-down," as shown in (Figure 1). Green synthesis, a bottom-up approach, has been considered the most successful method using a variety of plant extracts due to the drawbacks of some other methods, which use chemicals and produce harmful by-products. Reducing mineral feedstocks to nanoparticles using biosynthesis is a safe, economical, and environmentally friendly process that does not require the use of chemicals (Ansari et al., 2024). Plant-based nanoparticles (PNPs) represent a major advance in the field of bioremediation. The potential of phytocompound-adhered nanoparticles to remove contaminants such as biocides, polycyclic aromatic hydrocarbons, heavy metals, dyes, and pharmaceutical residues is being evaluated. Temperature, light exposure, agitation, pH, and other variables are controlled to maximize the size, shape, and characteristics of nanoparticles. To biodegrade heavy metals like arsenic and chromium in contaminated water (Pal et al., 2024).

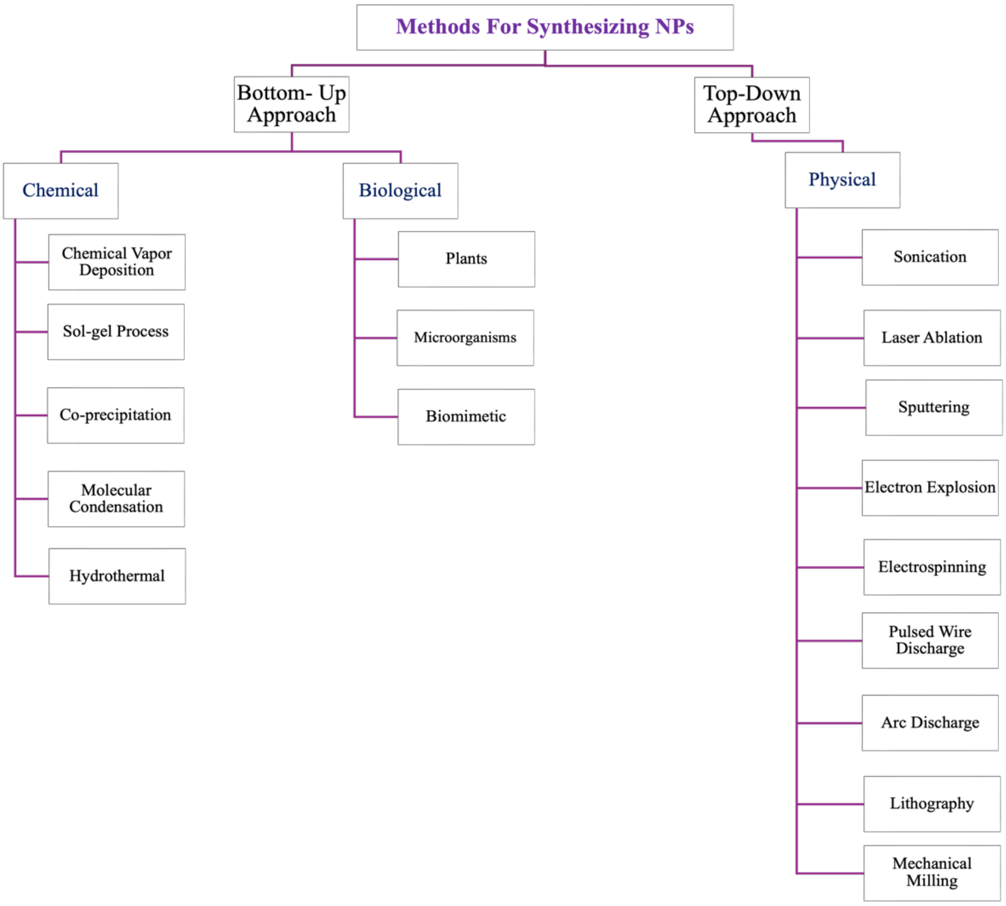

Figure 1: Different approaches for synthesizing nanoparticles.

In addition to the daily introduction of new photocatalytic materials with various properties for use in many industries, metal oxide photocatalysis with strong photocatalytic qualities is being promoted as a new technique for pollution control in the environment (Diallo et al., 2018). Metal oxide nanoparticles have been proven to be very useful in environmental cleaning, photocatalyst degradation, environmentally friendly agricultural chemicals, and antibacterial activity (Kamarajan et al., 2022). Many different kinds of contaminants are discharged into water bodies by a wide variety of enterprises. The most common toxic waste released by these productions is dyes, out of all the pollutants. The ecosystem and human health are at risk from dyes, even at very low concentrations (less than 1 ppm). It is possible to use green manufacturing of nanoparticles to break down dye molecules in wastewater. Many nanoparticles have been effectively used to remediate different dyes, such as methylene blue and rhodamine B (Pandey et al., 2020). The use of green manufactured nanoparticles to remove dyes from wastewater is a sustainable method that preserves the quality of our environment while preventing further pollution. On the other hand, the global issue of toxic metal ions in water is a major concern due to their human and environmental toxicity. The persistence, toxicity and bioaccumulation of heavy metals have made them a major environmental problem. The rapid development of industry, especially in emerging countries, has led to an increasing amount of waste containing heavy metals being released into the environment, either directly or indirectly. Heavy metals, unlike organic pollutants, are not environmentally benign and therefore accumulate in living organisms. Many heavy metals in their ionic state are lethal or carcinogenic (Kaur & Roy, 2021). Furthermore, nanoparticles has attracted much attention because it has been used to purify groundwater by eliminating microorganisms, heavy metals, and organic and inorganic substances (Gopal et al., 2022; Thilakan et al., 2022). Additionally, plant based nanoparticles are often recommended for use in the treatment of emerging pollutants. They are effective in detecting and extracting pollutants at low concentrations in aqueous solutions (Garg et al., 2024). However, the ability of nanoparticles produced from plant extracts to remove pollutants from aqueous solutions varies with their size and shape (Mystrioti et al., 2016).

Many plant nanoparticles (PNPs) have strong photoactivity, making them a promising solution for the removal of inorganic toxins from wastewater and the degradation of organic pollutants. This review investigates the various forms of photoactive plant-based nanoparticles and their uses in wastewater treatment.

Green Synthesis of Plant-Based Nanoparticles

Nowadays, a broad range of physico-chemical techniques are employed to create nanoparticles. Nevertheless, in biological and medical applications where NP purity is a key concern, biogenic reduction of metal precursors to yield matching NPs is employed. In these cases, a natural product extract with inherent stabilizing, growth-terminating, and capping properties is used in place of a reducing agent. The kind of biological entities that are present in different amounts as well as reducing chemical agents also affect the size and shape of NPs (Hussain et al., 2016).

Green synthesis techniques are advantageous in healthcare and environmental applications because they can reduce toxicity. Plants provide phytochemicals that are preferred for the synthesis of nanoparticles, such as flavonoids, terpenoids, polysaccharides, and phenolics (Widatalla et al., 2022). In the production process, when metal atoms gather to form clusters and subsequently NPs, natural substances serve as reducing agents and can stabilize NPs (figure 2). As a result, NPs may be precisely controlled in terms of size and shape, making them useful in a variety of applications. Green produced nanoparticles' efficiency, size, shape, and other characteristics are influenced by a number of variables, including pH, temperature, concentration, and time (Mittal et al., 2013). Achieving the intended nanoparticle properties and guaranteeing the synthesis process's repeatability depend on optimizing these variables. The stability of the nanoparticles and the reduction potential of the metal ions are influenced by pH. The size and shape of nanoparticles can be impacted by the varying activity of the functional groups involved in the reduction process at different pH values (Ahmed et al., 2016).

The kinetic energy of molecules is generally increased at higher temperatures, which speeds up the metal ion reduction reaction rate to nanoparticles. Extremely high temperatures, however, have the potential to denature biological agents and decrease their effectiveness, hence the temperature needs to be carefully regulated (Iravani, 2011). The concentration of metal ions, which is connected to the yield and size of the nanoparticles, is another crucial factor. Although they can sometimes result in particle agglomeration, higher concentrations usually result in more nucleation sites and a higher yield. The synthesis is also influenced by the quantity of biological extract (for example, plant extract) (Noruzi, 2015). Controlling the size and distribution of nanoparticles requires an ideal ratio between the biological extract and the metal ion solution (P. Singh et al., 2015). Green synthesis has become more attractive in the field of nanotechnology because the procedure is easy to repeat, safe, economical and sophisticated.

Characterization of these nanoparticles is crucial, and they are confirmed by a variety of instrumentation analyses, including atomic force microscopy (AFM), annular dark-field imaging (HAADF), scanning electron microscopy (SEM), transmission electron microscopy (TEM), Fourier transform infrared spectroscopy (FT-IR), atomic force microscopy (AFM), and intracranial pressure (ICP) (Vijayaram et al., 2024). Green synthetic metal nanoparticles are produced from different plant parts, and when compared to alternative techniques, these nanoparticles perform better in eliminating metal ions, dyes, and antibiotics (Ye et al., 2022).

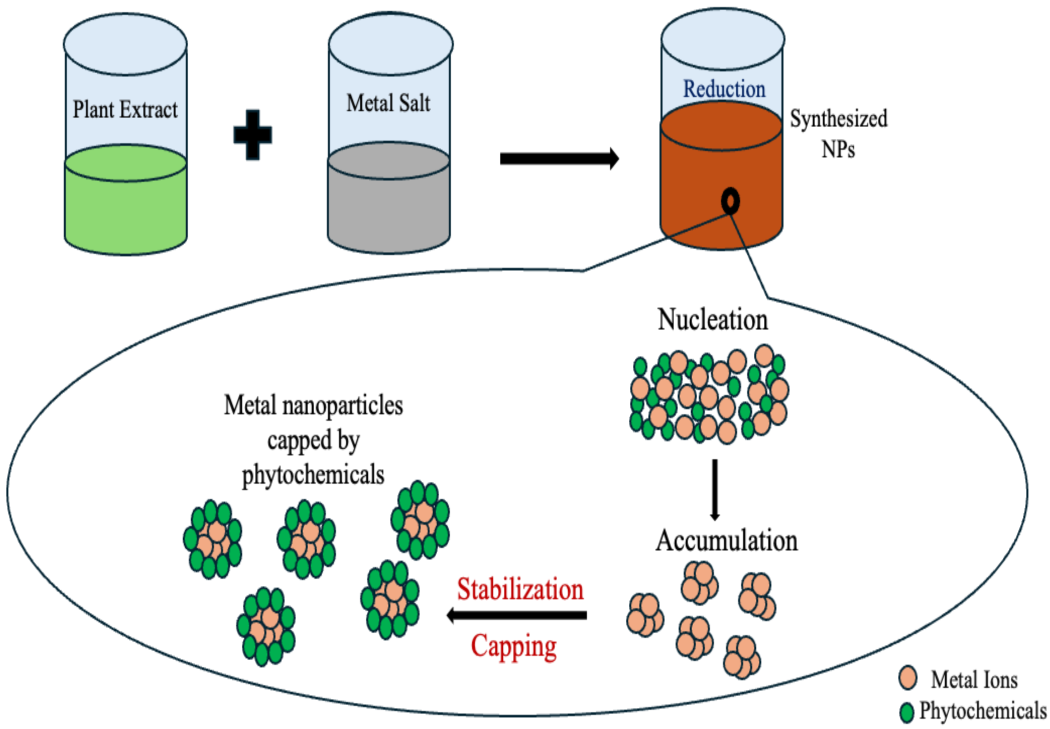

Figure 2: Mechanisms for the production of plant based nanoparticles

Photocatalytic Activity of Plant-Based Nanoparticles

One of the most important developments in green chemistry today is photocatalysis, an advanced oxidation method that is environmentally friendly (Borges et al., 2023). In other words, photocatalysis, a type of artificial photosynthesis, utilizes ecologically acceptable materials to address environmental and energy issues. Water filtering has made significant progress, and semiconductor-assisted photocatalysis has emerged as a promising way for producing ecologically benign energy. This green synthesis process outperforms chemical synthesis alternatives in terms of zero-waste. (Hassaan et al., 2023).

In detail, photocatalysis is a method that uses light energy to accelerate chemical processes, primarily in environmental cleanup. It includes the formation of charge carriers in semiconducting materials, which aids in the breakdown of pollutants in water, such as heavy metals and agricultural toxins. This approach is preferred for its low cost and efficiency, as it may function in ambient circumstances without emitting secondary pollutants (Sharma et al., 2022). In recent research, plant-based nanoparticles (NPs), have emerged as excellent photocatalysts due to their high durability and catalytic activity against organic pollutants (Premarathna et al., 2024).

Because photocatalysis is inexpensive, simple to use, has no byproducts, and effectively converts pollutants into CO_2 and H_2O, it has become a viable technique for breaking down water contaminants

(Song et al., 2021). In this advanced oxidation process (AOP), pollutants are broken down by reacting with a hydroxyl radical (·OH) produced in the presence of a photo-active catalyst, water, and a light source (Saravanan et al., 2017). The activation and migration of electrons from the valence band to the conduction band when the semiconductor material is exposed to light with an energy equal to the bandgap of the photocatalytic material initiates the photocatalytic degradation. The second stage involves the breakdown of organic compounds, usually contaminants found in wastewater, by hydroxyl radicals produced from water molecules by positive holes in the valence band (Gołąbiewska et al., 2018). Overall, photocatalysis offers a cost-effective and efficient method for decomposing water pollutants.

Nanoparticles with semiconducting properties, including advantageous electronic structure, charge transfer, and light absorption, are known as photocatalysts. Photoactive nanoparticles are used as catalysts in a number of processes, such as environmental cleanup and the production of renewable energy (Hassaan et al., 2021; Sahu et al., 2020; Saravanan et al., 2017; Spinelli et al., 2012). The positive aspects of employing plant nanoparticles as adsorbents are summarized in (Figure 3).

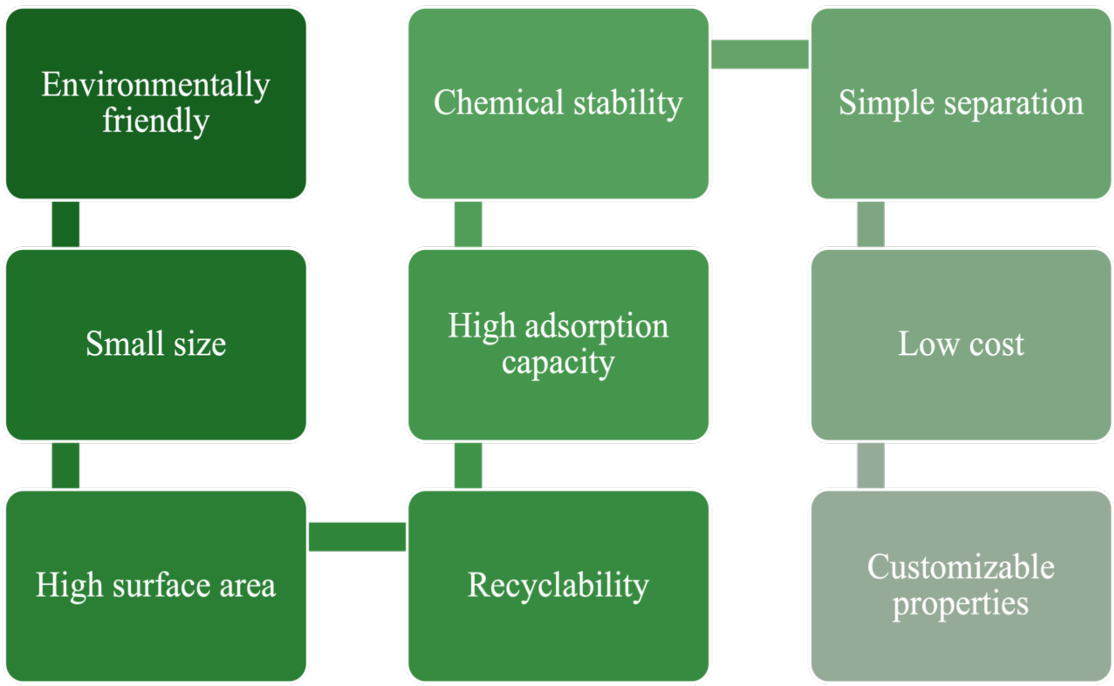

Figure 3: Advantages of using plant nanoparticles as adsorbents.

Compared to bulk materials, photocatalysts have better structures and larger surface area to volume ratios, which improve their activities (Christian et al., 2008; Yin et al., 2021).

Photocatalytic pollution remediation is a potential solution due to the abundant, inexpensive, clean, sustainable, and readily available light. Photocatalysis can easily destroy persistent organic pollutants by producing reactive oxygen species (ROS) (Mirzaeifard et al., 2020; Wang et al., 2009). To enable light-induced oxidation and reduction processes, new high-performance and photoactive nanomaterials are needed. Sunlight is a vital source of energy for humans, with photosynthesis being the most common way to convert solar energy into usable energy. The total solar radiation power is 384.6 watts, and the exposed parts of the Earth receive about 1368 W m^{-2} (Foster et al., 2009; Janani et al., 2022). About 1000 W/m2 of solar energy is received everywhere on the Earth's surface due to the atmosphere reflecting 30% of the solar radiant energy. However, the challenge lies in harvesting this energy and using it efficiently. (Hassaan et al., 2023). Researchers can pave the road for more environmentally friendly and effective water treatment solutions by further refining green synthesis methodologies and photocatalytic applications.

Applications in Water Remediation

Plant-based nanoparticles have great potential for photocatalytic use in treating various types of water pollutants. Figure 4 summarizes some of the most important applications. Some of the most important applications are summurize in (figure 4).

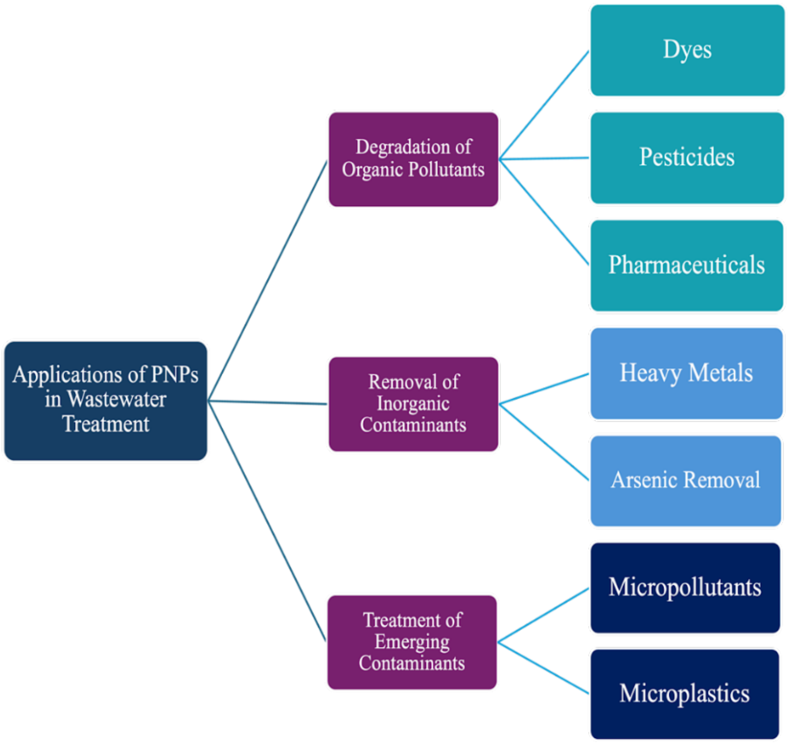

Figure 4: Applications of plant-based nanoparticles (PNPs) in wastewater treatment.

The following are some of the most extensively researched nanoparticles for photocatalytic applications:

Silver Nanoparticles (AgNPs):

Silver nanoparticles (Ag NPs) have strong microbicidal action against a variety of microorganisms, such as bacteria, fungus, and viruses, due to their exceptional toxicity to microorganisms (Bruna et al., 2021). Additionally, they are effective choices for removing pollutants including methyl orange, Congo red, and rhodamine that are frequently found in wastewater bodies because to their enhanced adsorption capacities (Ganguly et al., 2021). The sensor performance was improved using silver nanoparticles, synthesized using plant extracts according to a green synthesis approach. These nanoparticles can be used as sensors for monitoring water pollutants (Serunting et al., 2023). Numerous studies have demonstrated the promising potential of plant-based AgNPs for use in water remediation applications. Using extract from *Leucaena leucocephala*, silver nanoparticles were created and evaluated for their capacity to enhance adsorption and clean up water contaminated by tartrazine and methylene blue. Neither special lights nor direct sunlight exposure are necessary for these nanoremediations. Leaf-derived AgNPs were the most effective in nanoremediation and exhibited antioxidant activity, making them a promising nanotool for antioxidant nanostructure and dye nanoremediation (Silva et al., 2024). Similarly, *Lawsonia inermis* leaf extract was used to create a novel silver nanoparticle for wastewater treatment. It showed superior catalytic degradation ability for organic pollutants such as 4-nitrophenol, methylene blue, eosin yellow, and methyl orange. It achieved an impressive dye removal of 82.5% with a catalytic loading of only 0.2 mg/mL, providing an economical and environmentally friendly option for water purification applications (Natrayan et al., 2024). Using a leaf extract from *Eucalyptus globulus*, AgNPs with photocatalytic activity were created, decomposing the dye indigo carmine (IC) up to 98% efficiently in the presence of sunlight. The antibacterial properties of the nanoparticles were also shown against *Escherichia coli* and *Staphylococcus aureus* (Rocha et al., 2023). Likewise, AgNPs produced with *Ammi visnaga* and *Trigonella foenum-graecum* showed photocatalytic effectiveness, breaking down toxic dyes and biofilms while enhancing water quality indicators including pH, chemical oxygen demand (COD), biological oxygen demand (BOD) (Farooq et al., 2023). Moreover, using wheat (*Triticum aestivum*) and corn (*Zea mays*), the green synthesis of silver nanoparticles was investigated and its effects on plant growth and organic pollution decontamination. AgNP treatments of three different kinds were tested: T1 (wheat-based), T2 (corn-based), and T3 (a combination of the two). Ag0 made up 44% of T1 and 66% of T2. At 40 μg mL^{-1}, T1, T2, and T3 all decreased methylene blue absorbance by 43.3%, 47.4%, and 49.7%, respectively; T3 was the most effective (Abbas et al., 2024).

All of these research demonstrate how plant-based AgNPs can be used as environmentally friendly wastewater treatment agents that efficiently remove both organic and inorganic pollutants.

Zinc Oxide Nanoparticles (ZnO NPs)

According to reports, zinc oxide nanoparticles (ZnO NPs) have potent photocatalytic capabilities that rely on surface hydroxyl radicals, UV radiation, and energy sources (Bhattacharjee et al., 2024; Vasantharaj et al., 2021). Due to the high exciton binding energy and wide band gaps, the photocatalytic potential of ZnO NPs is strong (R. T. Hussain et al., 2024). Combining ZnO nanoparticles with plant extracts significantly increases their photoactivity. ZnO nanoparticles made with beetroot, for instance, demonstrated an amazing 87% breakdown efficiency of methyl orange when exposed to UV light (Ahmed et al., 2024).

In addition ZnO NPs as promising agents for addressing bacterial biofilms, textile dye degradation, and plastic waste in water purification efforts. Green, environmentally friendly ZnO NPs were produced for water purification applications using an extract of Areca catechu (areca nut). At a concentration of 50 μg/mL, the ZnO nanoparticles had a potent antibacterial action, particularly against E. coli, preventing the formation of biofilms. The nanoparticles also showed good photodegradation of the dyes methylene blue, nigrosin, and rhodamine-B when exposed to sunlight (Raghavendra et al., 2022). For antibacterial and bioremediation applications, green ZnO NPs were synthesized using *Ruellia tuberosa*. Higher antibacterial action was demonstrated by ZnO NPs against Gram-negative bacteria, particularly Escherichia coli. Additionally, ZnO NPs were applied to textile materials to stop Escherichia coli from growing. From an environmental point of view, ZnO NPs broke down malachite green (MG) and methylene blue (MB) by 92% and 94%, respectively (Vasantharaj et al., 2021). ZnO NPs are therefore used in the textile sector to suppress harmful germs and degrade synthetic dyes. Plant-based ZnO nanoparticles using Citrus limon leaf extract have been shown to be effective in water treatment by exhibiting strong antibacterial activity against harmful Gram-positive and Gram-negative bacteria (K. Singh et al., 2023). Given the fact that heavy metals and chemical pollutants in petrochemical wastewater constitute a major environmental problem, their disposal is required to protect aquatic life, hydrosphere systems and biodiversity. Nanoparticles of α-Fe_2O_3, CuO and ZnO were produced using

Portulaca oleracea leaf extract, and their appearance, content and crystal structure were characterized. When these nanoparticles were used as adsorbents, they were able to remove As(III), Bi(II), Cd(II), Cr(VI), Mn(II), Mo(II), Ni(II), Pb(II), Sb(III), Se(-II) and Zn(II) from wastewater with 100% removal efficiency under ideal conditions. There is potential for the use of photocatalytic techniques in the purification of water contaminated by hydrocarbons, as it has demonstrated the ability to eliminate heavy metals and clean water of all suspended contaminants (Bouafia et al., 2023). In order to extract metal ions (Cd^{2+} and Pb^{2+}) from aqueous solutions, ZnO nanoparticles were effectively synthesized from mangrove leaf extract. The resultant crystals had broad peaks and significant UV absorption at 370 nm. With a high adsorption capacity and regeneration efficiency, the adsorption of Cd^{2+} and Pb^{2+} was studied. Compared to Cd^{2+}, Pb^{2+}showed higher selectivity. Five minutes was the ideal contact time for Pb^{2+} removal, with removal efficiencies exceeding 79.52 and 69.51%, respectively (Al-Mur, 2023).

ZnO semiconductor development, especially those made with plant extract, and its ability to remove pollution by adsorption, reduction reactions, and photocatalytic degradation. The photocatalytic activities of ZnO can be enhanced by doping with transition metals and forming heterostructures, as well as by using plant extract in the manufacturing, decreasing charge carrier recombination, and enhancing the specific area. When compared to ZnO, the optical properties of ZnO-based nanocomposite tend to deteriorate. The morphology has fine structure and is observable. Due to the use of plant extracts in the production, the agglomeration of nanoparticles can be avoided (Zelekew et al., 2023).

Titanium Dioxide Nanoparticles (TiO_2 NPs)

TiO_2 NPs are efficient photocatalysts that may break down organic contaminants such dyes, medications, and phenolic chemicals when exposed to UV and visible light. They are non-toxic, affordable, and have superior optical, electronic and catalytic properties. The ability of titanium dioxide nanoparticles to improve water quality has been demonstrated through their successful application in thermally produced polymeric membranes. Research indicates that TiO_2 NPs are effective in treating water because they can degrade pollutants like Methylene Blue and 17α-ethinylestradiol by more than 90% (Inamdar et al., 2024). The green TiO_2 NPs excelled chemically produced TiO_2NPs in terms of photocatalytic activity and efficiency when it came to the photodegradation of Methyl Orange (MO) organic dye (Mousa et al., 2022).

Moreover, the efficiency of titanium dioxide nanoparticles made from extracts of Chenopodium quinoa and Trianthema portulacastrum in eliminating the heavy element cadmium from wastewater was compared. The outcomes confirm that TiO_2 NPs can be used to remove high quantities of liquified cadmium from industrial wastewater (Irshad et al., 2022). Using Syzygium aromaticum (SA) bud extract to create titanium dioxide nanoparticle in an environmentally friendly manner. Compared with conventional photocatalysts, the nanoparticles have special properties and are highly effective in degrading bright yellow (BY-18) dye. At a low dose of SA-TiO_2, the nanoparticles removed 93.6% of BY-18 dye in 60 min. This has highlighted how natural resources can be used to provide advanced synthesis of nanoparticles with enhanced functionalities for photonic applications (P. Kumari et al., 2024). Utilizing durva plant waste extract to create titanium dioxide nanoparticles, enabling stability and size control. These different-sized nanoparticles have the ability to quickly and efficiently degrade industrial textile dyes like rhodamine B and methylene blue (Palajonnala Narasaiah et al., 2022). Furthermore, the efficient removal of arsenic (As), copper (Cu), and cadmium (Cd) from copper mine effluent by using TiO_2 to increase the phytoremediation capability of *Lemna minor*. TiO_2 NPs application significantly increased plant biomass and growth metrics, suggesting that they can enhance plant health in contaminated conditions. This further highlights the potential of TiO_2 NPs to improve arsenic and copper removal and the importance of incorporating TiO_2 NPs into phytoremediation technologies for the effective treatment of heavy metal contaminated water in general. (Seifi & Dehghani, 2021).

Similarly, green TiO_2 NPs were synthesized using the aqueous extract of *Polycaria undulata*, and showed almost complete degradation of methylene blue and methyl orange under UV-visible light irradiation (Al-hamoud et al., 2022). Leaf extract from *Syzygium cumini* is used as a capping ingredient in green production titanium dioxide nanoparticles. The ability of these nanoparticles to remove lead from industrial effluent by photocatalysis was evaluated. The findings revealed an 82.53% lead removal rate and a 75.5% chemical oxygen demand elimination rate (Sethy et al., 2020).

Copper Oxide Nanoparticles (CuO NPs)

Copper oxide is an attractive photocatalyst for water and wastewater treatment due to its low cost and environmental friendliness. It efficiently destroys pollutants by producing reactive radicals. However, its performance is limited by rapid recombination and slow charge carrier mobility (Sibhatu et al., 2022). Moreover, copper oxide is one of the most popular reference photocatalysts for photodegradation because of its exceptional absorption efficiency throughout a wide range of the solar spectrum (Raizada et al., 2020). Congo red dye degradation, supercapacitor energy storage, and antibacterial activity were investigated using CuONPs nanoparticles prepared using Betel leaf (*Piper betle*) extracts. The NPs demonstrated a maximum 89% photodegradation of Congo red dye and, demonstrating their potential against *Bacillus subtilis* and *Pseudomonas aeruginosa* (Ahmad et al., 2024). In addition green nanoparticles of zinc oxide and copper oxide were investigated using *Calotropis gigantea* leaf extract and were 80.53% effective with CuO and 78.25% effective with ZnO in removing methylene blue dye from wastewater (Velusamy et al., 2024). The use of green synthesized CuONPs derived from *Platanus occidentalis* leaf extract in water disinfection has been demonstrated to be effective, showing high adsorption capacities for thiazolyl blue and paracetamol (Akpomie & Conradie, 2023).

Green-synthesized copper oxide nanoparticles using *Hibiscus sabdariffa* extract have proven effective in wastewater treatment as they eliminated 26% of the chromium, 78.8% of the copper, and 78.2% of the chloride, decreased total dissolved solids and conductivity by 99%, and decreased chemical and biological oxygen demands by 56% (Almisbah et al., 2023). And the green-synthesised CuO nanoparticles using *Portulaca oleracea* shown notable catalytic and antibacterial properties, especially in wastewater treatment. CuO-NPs successfully decreased the levels of pollutants in tanning wastewater, reducing conductivity, chemical oxygen demand (COD), biological oxygen demand (BOD), total suspended solids (TSS), and total dissolved solids (TDS) by more than 85%. There was also a 64-91% reduction in heavy metals such cobalt, lead, nickel, cadmium, and chromium (Eid et al., 2023). Similarly, CuO NPs were synthesized in a green way using mint and orange peel extracts. A number of factors, including contact time, nanosorbent dosage, pH, and metal ion concentrations, have been shown to control the use of CuO NPs as one of the frequently used nanoparticles for removing nickel, lead, and cadmium from contaminated water (Mahmoud et al., 2021). A green synthesis method of CuONPs was developed using *Aloe Vera* and *Gundelia tournefortii* extracts for heavy metal adsorption. The nanoparticles exhibited high photocatalytic activity, eliminating the heavy cation Pb^{2+} with an efficiency of over 99% (ChizariFard et al., 2022). According to these findings, CuONPs are a viable environmentally friendly wastewater remediation method.

Iron Nanoparticles (FeNPs)

Zerovalent metal nanoparticles have demonstrated their efficacy in the remediation and treatment of tainted water in recent years. According to reports, nanoscale zerovalent iron (nZVI) has garnered a lot of attention as a possible innovative adsorbent for the treatment of several heavy metals, such as cadmium (II), nickel (II), copper (II), chromium (VI), and mercury (II). The large specific surface area and high reduction capacitance of nZVI are responsible for its exceptional adsorption capability (Huang et al., 2013). Green technologies for the production of zerovalent iron nanoparticles show promise in water treatment, especially when it comes to the removal of heavy metals such as lead, copper, chromium, and cadmium from wastewater. In addition to making these NPs more environmentally friendly, the use of natural plant extracts also increases their effectiveness as they contain organic chemicals such as flavonoids and polyphenols that provide spatial stability. The high surface area and reducibility of these nanoparticles enable efficient adsorption and reduction of heavy metals, making them highly effective at low pH levels and at higher doses. Several studies highlight how green-processed iron nanoparticles can be a viable and effective approach for the removal of heavy metals from water treatment applications (Thilakan et al., 2022).

Six distinct plant extracts are used as reducing agents in the environmentally friendly manufacture of iron nanoparticles. Depending on the plant extract utilized, the photocatalytic activity of the produced FeNPs was shown to be effective in degrading gentian violet dye under visible light, with removal efficiencies varying from 40% to 83%. Interestingly, the best efficiency of dye degradation and nanoparticle generation was obtained from *Ocimum sanctum* extract. The results demonstrate the promise of these iron nanoparticles for efficient water treatment applications by showing that they have strong antibacterial and photocatalytic qualities, cheap production costs, and high adsorption capabilities (T. Kumari et al., 2023). Greenly produced iron NPs hold significant promise for water remediation. They are effective and cost-effective techniques to dealing with water contamination because of their strong ability to absorb heavy metal ions such as Cd^{2+} and Ni^{2+}. The antibacterial capabilities of iron nanoparticles make them more useful in wastewater treatment because they reduce the potential microbial burden (Mohamed et al., 2023). Effective removal rates of 82% and 77% for lead and cadmium, respectively, were demonstrated by the green production of iron oxide nanoparticles utilizing *Ramalina sinensis* (Arjaghi et al., 2021).

In conclusion, the use of green-synthesized nanoparticles provides a potential way to improve water quality and reduce environmental pollution, which necessitates further research and development for practical industrial applications.

Obstacles and Prospects

Despite the positive results achieved by plant nanoparticles in water cleaning, several obstacles remain. A major challenge is scalability; while green manufacturing processes are environmentally friendly, scaling up the production of nanoparticles to meet industrial demand remains a challenge. Furthermore, the environmental and physiological consequences of nanoparticles during water treatment need to be comprehensively investigated. The potential for nanoparticles to accumulate in the environment or on living organisms raises long-term safety concerns. To address these issues, future studies should focus on:

Enhancing formulation efficiency: Finding ways to produce more plant nanoparticles while maintaining their environmental suitability. Evaluating impacts over time: Investigating the environmental and human health impacts of using nanoparticles in water treatment in greater detail. Integration with existing systems: Investigating ways to integrate plant nanoparticles into existing water treatment infrastructure to improve their overall effectiveness.

Conclusion

The sixth goal of the 2030 Agenda for Sustainable Development is to combat water pollution, which poses a serious threat to ecosystems, economies, and human health. Conventional approaches have drawbacks, including high costs and energy-intensive procedures. Bioremediation of water enhanced with PNPs offers an environmentally friendly alternative and a promising long-term solution to the growing problem of water pollution. These nanoparticles can degrade a variety of organic and inorganic pollutants, including dyes, pesticides, pharmaceuticals, heavy metals, and new toxins, due to their strong photocatalytic activity. Green nanoremediation has the potential to revolutionize water treatment systems, but scalability and environmental safety issues remain. By advancing green synthesis methods and photocatalytic applications, researchers can create more effective and sustainable water treatment solutions.

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Biocontrol Agents to Mitigate Fusarium graminearum Species Complex Causing Fusarium Head Blight in Cereal

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Abstract

The *Fusarium graminearum* species complex is a collection of mycotoxigenic fungi representing serious risks for small grain crops worldwide. These fungi primarily affect wheat, barley, maize, and rice crops. They cause wheat Fusarium head blight (FHB), which leads to significant production losses and economic consequences. Fusarium species linked with FHB in cereals have recently become serious and widespread, resulting in a major yield decrease, yield loss of up to 100% during a severe epidemic in wheat, and mycotoxin contamination (deoxynivalenol) of wheat grain across the continent. Because FHB is caused by the *Fusarium* species complex, alternative, practical, low-cost, and environmentally safe disease control techniques are necessary to address many pathogenic *Fusarium* species successfully. Among these methods, the use of biocontrol agents (BCAs) as synthetic fungicide substitutes to control *Fusarium* complex species of FHB in cereals has drawn attention. Biological management of phytopathogens is gaining attention from the standpoint of the microbiome. BCAs are naturally occurring organisms or their derivatives that combat phytopathogens. These microbes suppress, inhibit, manage, or reduce the effect of the pathogen and its metabolites, lowering the disease's survival or activity. This paper aims to emphasize the present insight into the microbiome of cereal crops and how it relates to mycotoxin contamination, FHB infection, and management. It also looks at protocooperation between cereal crop genotypes and biocontrol agents as a potential strategy against FHB.

Keywords: Biocontrol, cereal, microbiome, *Fusarium graminearum* species complex
Discipline: Crop Protection, Phytopathology

Introduction

Over the next century, there will likely be a surge in the global need for food [1]. Cereal crops, including maize, rice, and wheat, are extremely significant worldwide. Together, they account for more than 32% of global agricultural production[2]. Cereal crops are an important host for particularly pathogenic *Fusarium* species complexes across the globe. Microbial biocontrol has gained significance recently as a long-term disease management tool. But before microbial biocontrol can be applied in agriculture, it will be necessary to comprehend how microbiota affects plant performance in general and how they differ depending on the host's innate resistance to disease. Therefore, it is imperative to adopt sustainable farming methods that improve food security while reducing the need for artificial fertilizers and pesticides [3]. Growing evidence points to the application of microbial inoculants in agriculture as a means of raising crop resistance to plant diseases, especially the severe fusarium head blight that affects cereals, and enhancing crop yields.

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The increasing epidemic of *Fusarium* disease is expected to coincide with the continuous worldwide intensification of cereal crop production[4]. One of the most significant diseases affecting cereals including wheat is Fusarium head blight (FHB), which results in lower yields and mycotoxin contamination of cereal crop grain after harvest. FHB is caused by a complex of many toxic *Fusarium* species, and agronomic and climatic variables influence the species' abundance and composition within the complex[5]. Fusarium fungi are recognized globally as plurivorous diseases (living upon several hosts) of a wide range of crops. Numerous coexisting species that infect maize and small-grain cereals including wheat, barley, oat, rye, rice, and triticale are the source of fusarium diseases. Many species cause ear rot in maize and FHB, commonly known as scab or ear blight, on small-grain cereals and roots, stems, and seedlings, respectively[6], [7], [8].

Fusarium toxins, which are dangerous for both human and animal health and seriously threaten the safety of food and feed are frequently present in infested grains. Within the Fusaria genus, more than 70 species of *Fusarium* have been discovered so far. On wheat, maize, and other plants, *Fusarium graminearum* species complex (FGSC), *F. verticillioides, F. culmorum, F. oxysporum, F. solani, F. proliferatum, F. poae, F. equiseti, and F. fujikuroi* are the most often isolated species globally. It is important to note that these fungi can produce a large range of mycotoxins. The most common Fusarium mycotoxins found in cereal grains are deoxynivalenol (DON), zearalenone (ZEN), and fumonisin B1 (FB1) and are critical to the safety of feed and food. It is now evident that many species of fungus may create the same mycotoxin, and that a single fungus species can produce a wide variety of mycotoxins. For instance, FGSC can make zearalenone and trichothecene, but *F. culmorum, F. poae,* and *F. equiseti* can all produce trichothecene[9].

One approach to integrated disease management (IDM) is the use of biocontrol with other management options. The synthesis of phytohormones, essential to the plant defense system, can be stimulated by pathogenic microbes, remarkably by bacterial and fungal biocontrol agents. In addition, reducing the pathogen inoculum of FHB by biological management, such as treating agricultural residues with antagonists, has a great deal of potential[10], [11].

There are limited or no reliable and efficient methods of controlling *Fusarium*. Furthermore, commercial cultivars only partially exhibit resistance. Fungicide usage and agricultural practices like rotation to lower disease incidence are the mainstays of disease control[12]. The efficacy of the chemical treatments varies depending on the kind of fungus species involved, and they may change the positive roles of microorganisms in the soil and rhizosphere ecosystem, posing a danger to human and animal health and increasing environmental pollution. Biological control agents are now recognized as an environmentally acceptable substitute. It is among the most promising technologies for controlling *Fusarium* spp. and preserving the present level of agricultural productivity [13], [14].

Crop resistance mechanisms have received much attention in the last century when discussing the FHB outbreak, caused by the FGSC in wheat and other cereal genetic factors that influence the disease's progression. While research on FHB and genetics in cereal crops is more advanced than on biocontrol, new improvements have highlighted the significance of beneficial biocontrol agents (BCAs) in influencing disease development. Thus, given present management practices and changing climate circumstances, it would appear helpful to make a more concentrated and intentional effort to investigate the protocooperation between BCAs and resistant wheat genotypes. Within a well-defined integrated management plan, the combined breeding and biocontrol effort might yield and add another weapon to the resistance armory in the fight against FHB[15].

It is thought that the microbiome, which acts as the second genome of the plant, can lessen *Fusarium* virulence, although it is unclear if other plant-associated properties, such as wheat characteristics based on the microbiome, are related to host resistance [16]. Studies have shown that cereals' microbiome can, without genetic change, prevent *Fusarium* pathogen infection [17] or give resistance [18]. This review summarizes the current knowledge of the cereal crop microbiome and its relationship to mycotoxin contamination, FHB infection, and management. It also examines the possibility of using biocontrol agents and cereal genotypes in protocooperation to combat FHB.

FHB and Fusarium Ear Rot (FER) caused by FGSC in Cereal Crops

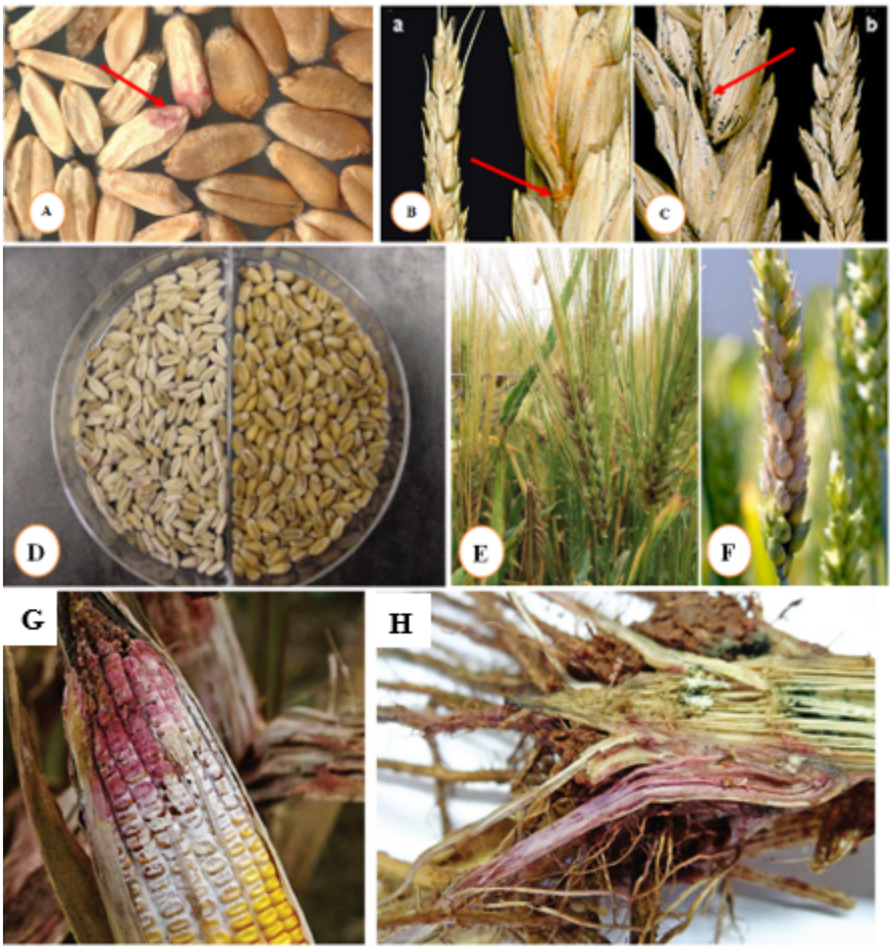
Worthington G. Smith of England initially described FHB in his book *Diseases of Field and Garden Crops*, published in 1884 [19]. Since then, the disease, which primarily affects cereal crops, has been better described. It began as a concise but thorough explanation of the symptomology in W.G. Smith's book and has since evolved into an intricate disease that has devastated the global cereal crop business over the past century. Currently endemic to several regions of Africa, Asia, Europe, South America, and North America, even this disease caused significant outbreaks in Ethiopia in the early 21st century [20], [21], [22], [23], [24], [25], [26]. It was also reported and is becoming a serious disease in some regions of Turkey [27], [28], [29], [30]. Yet since multiple *Fusarium* species are responsible for the FHB disease in cereals, data collecting and breeding for resistance remain challenging. *F. chlamydosporum, F. boothii, F. scirpi, F. arthrosporioides, F. poae, F. avenaceum, F. culmorum, F. graminearum, F. verticillioides, F. asiaticum,* and *F. cortaderiae* are a few of the more well-known species [31].

Disease symptoms appear on the head, grain, and, in certain cases, the peduncle (neck). Typically, the first visible indication is bleaching of some or all the spikelets, while healthy heads remain green. As the fungus spreads along the rachis, spikelets above or below the initial infection location may become bleached. The symptom in barley is slightly different; the infected spike is positioned and does not spread to the spike's rachis. Pink to orange spore masses may be observed on infected spikelets under humid and moist conditions. FGSC symptoms are also observed on maize cobs which cause cob or ear rot (FER) and discoloration of root tissue in maize crops (Figure 1).

Utilizing cutting-edge technology advancements including polymerase chain reaction (PCR), multilocus genotyping (MLGT), and next-generation DNA sequencing platforms, the complex has undergone many updates throughout the years [32], [33], [34], [35], [36]. FGSC also called *F. graminearum sensu lato*, has 16 formally identified phylogenetically different species, according to recent molecular advances [26], [32], [33], [35], [36]. *Fusarium graminearum sensu lato* is a species complex within the genus ***Fusarium*.** It is a significant fungal pathogen known to cause FHB in cereals, particularly wheat and barley. This disease can lead to considerable yield losses and contamination of seeds with mycotoxins, which are harmful to humans and animals. Globally, these are some of the most significant species that cause FHB [37], [38].

The most prevalent species in each global agroecological zone are closely correlated with location. Ethiopia is inhabited to plenty of FHB-affected locations; in recent years, the disease has become widespread in almost every of the country's key wheat-producing regions [21], [39], [40]. In Ethiopia, *Fusarium graminearum* was the most common species, although other species associated with FHB of wheat include *F. culmorum, F. avenaceum,* and *F. poae.* The most widespread species in country like Kenya on the African continent include *F. graminearum, F. poae,* and *F. chlamydosporum* [41]. In Turkey, the Marmara Region has been experienced with FHB epidemic in 1997 and 1998. Fifteen *F. graminearum* and *F. culmorum* are common species that cause FHB disease throughout the nation, and they were isolated from diseased spikelets of wheat in the Marmara Region [42]. *F. graminearum* is the most common species in diseased crops in Eastern Asia's colder parts of North Japan, whereas *F. asiatium* is more common in the region's dry south [43]. Similar trends are also observed in China, where *F. asciatium* predominates in the South while *F. graminearum* is the most common pathogen in cereals in the North [44]. However, in the majority of instances, it was observed that *F. graminearum* was the predominant cause of FHB in many European nations [45]. In Europe, a complex of species, including *F. graminearum, F. avenaceum, F.culmorum,* and *F.poae*, are mostly linked to FHB. Over the past few decades, *F. graminearum sensu stricto* has been identified as the main aetiological agent of FHB epidemics in both North and South America (Argentina, Brazil, and Uruguay) [23], [24], [25], [46]. *F. culmorum* and *F. poae* are two more significant Fusarium species found in North America [33], [47].

Figure 1.*Head blight symptoms on wheat, barley, and maize and Fusarium ear rot (FER). (A, D) small, shriveled pale white appearance and sometimes pink, infected (left)and healthy (right), (B, C) Orange sporodochia and Bluish black perithecia are formed at the base of the glumes, (E, F) Premature bleaching of Barley and wheat spikes, (G)Gibberella ear rot caused by* ***Fusarium graminearum*** *species complex, (H)The characteristic pink discoloration of root tissue infected by the* ***Fusarium graminearum*** *species complex.*



Source: Matny 2015 [48]

Mycotoxigenic *Fusarium* Pathogens

Mycotoxigenic *Fusarium* pathogens are a group of fungi within the genus *Fusarium* that produce myc otoxins, which are toxic secondary metabolites. These pathogens can infect a variety of crops, includin g cereals like wheat, barley, oats, and maize, as well as other plants such as bananas and tomatoes. The mycotoxins they produce can pose serious health risks to humans and animals and lead to significant economic losses in agriculture due to reduced crop yields and quality [49], [50]. Type B trichothecenes, deoxynivalenol (DON) and its acetylated derivatives 3 ADON and 15 ADON, nivalenol (NIV), and zearalenone (ZEN) are all produced by the extremely aggressive hemibiotrophic pathogen *F. graminearum* [9], [51], [52], [53]. These are a few of the most significant fungi found to contaminate crops, including cereal grains, that are processed for use by humans and animals. DON is the most common and called vomitoxin, which humans and animals encounter when exposed to different concentrations of DON [12], [54]. Research has proven that Pig weight loss and feed refusal have been connected to DON[55]. After consuming contaminated food, DON is the causative agent in human cases of vomiting, diarrhea, neurological abnormalities, liver and kidney damage, immune system impairment, and impaired nerve system [56].

DON acts as a virulence factor, enhancing the pathogen's ability to infect and spread within the cereal heads, leading to more severe Fusarium head blight infections and significant yield losses[57]. The rel ationship between DON levels and visible *Fusarium* Damage **(**FUS DMG**)** in wheat has been extensiv ely studied. Research indicates a positive correlation between the two: as DON levels increase, the sev erity of visible *Fusarium* damage also tends to increase. This means that higher concentrations of DO N are often associated with more extensive Fusarium head blight symptoms, such as shriveled kernels and premature bleaching of the spikelets [58].

Apart from type B trichothecenes like DON, a wide range of additional mycotoxins such as Type A trichothecenes and fumonisins are often found in mycotoxins of *Fusarium* species found in infected cereal grains. Fumonisins—FUM of (*F. vericillioides* and *F. proliferatum*), aurofusarin-AUS (*F. graminearum, F. poae,* and *F. sporotrichoides*), type A-trichothecenes, T-2 and HT-2 are commonly produced by (*F. poae*), beauvericin and enniatins (*F. avenaceum, F. poae,* and *F. sporotrichoides*), and moniliformin (*F. proliferatum* and *F. subglutinans*) are mostly commonly produced secondary metabolites of (*F. graminearum* and *F. culmorum*) [56], [56], [59], [60]. Nevertheless, the most common mycotoxins found in cereal grains are type B trichothecenes, DON, and its acetylated derivatives 3 and 15 ADON that are produced by *F. graminearum* and *F. culmorum*. Therefore, a better understanding of these toxins and how to reduce them in grains is crucial to the stability of the agri-food industry and the sector that produces cereal crops. Developing a sustainable management strategy to control the toxigenic *Fusarium* species complex and related FHB damage can benefit from an understanding of how and what influences the alteration in the type and level of mycotoxins.

Management of FGSC Causing FHB

Before and after-harvest treatments are typically used to classify the preventive measurements of FHB and Fusarium mycotoxins in Africa, Asia, Canada, the United States, China, Europe, and other major wheat-producing nations global. Agronomic techniques include crop rotation and no-till, genetic modification-based breeding and host optimization, chemical, and biological treatments, and FHB forecasting are a few of the most widely used techniques. Furthermore, a few natural parasites of the *Fusarium* fungi have been studied throughout the past 20 years [16], [22], [52], [54], [61], [62], [63], [64], [65]. The various FHB management techniques that have been employed during the previous 50 years are now well-covered by innumerable publications, reviews, and critiques. Here are some fast and thorough guides on some of the most often used and successful techniques: Wegulo 2015 [12], Legrand 2017 [54], McMullen 2012 [22], Gilbert and Tekauz 2011 [66], Mielniczuk 2020 [67], Wang et al 2020 [68],Palazzini et al 2022 [69] and Yeo et al 2024 [70]. The majority of the conventional management techniques discussed in these papers have had encouraging outcomes, but none of them have been accepted as a long-term cure for FHB except few [71], [72], [73].

Although the actual reductions are highly variable, chemical treatment, including the widely used demethylation inhibitor (DMI) class fungicides such as metconazole (Caramba), prothioconazole plus tebuconazole (Prosaro), and tebuconazole (Folicur), results in no greater than 60% control of FHB and 30% to 50% of DON in wheat [22], [74]. As past events have demonstrated, fungicide resistance eventually develops due to overusing these fungicides [64], [75], [76]. Concerns have also been raised regarding toxicity and associated environmental and health risks [52], [71], [77].

Many scientists have long argued that the best strategy for managing FHB in cereals and other crops is host resistance [62], [78], [79]. Nevertheless, hardly much fusarium resistance has been discovered despite screening thousands of wheat lines. It has not been simple to optimize host resistance in common wheat and durum since resistance to FHB is a complex, quantitatively inherited characteristic that is influenced by environmental conditions and controlled by multiple genes [61], resulting in a very sluggish rate of genetic gain per unit of time [52]. Host or genetic resistance is thought to be the safest and most economical method of establishing long-term control against FHB, despite all these obstacles. The same source also stated that after screening 70,000 hexaploid wheat and related accessions gathered globally, it was possible to identify 7000 accessions with varying degrees of FHB resistance. Roughly 10,500 accessions of the durum and common wheat subspecies, as well as their close relatives Emmer, Oats, and Einkorn, have been examined for FHB resistance. Nonetheless, only a small number of accessions have been shown to exhibit different degrees of FHB resistance [80].

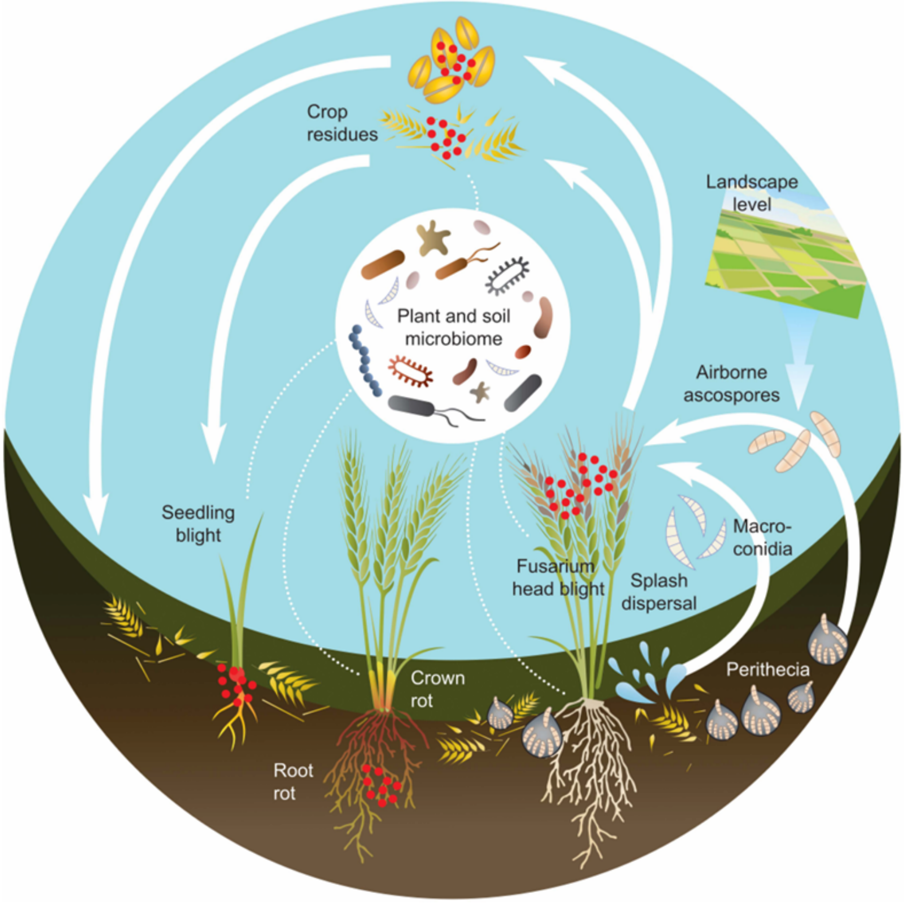
Management of FGSC Using Biological Control Agents

Using microbiome techniques in current worldwide breeding projects is another intriguing tactic [81]. The significance of plant pathogens and the interactions between the plant microbiome is increasingly being recognized, with a focus on pathogenic and mycotoxigenic Fusarium species[82]. There is growing interest in adopting biological control to combat plant infections from the standpoint of the microbiome. The use of live creatures to limit the growth and proliferation of other undesired ones is referred to as biocontrol in general [53], [83].These living organisms, which are suitably named biocontrol agents (BCA) [53], [54], [84], especially bacteria and fungi, decrease a pathogen's ability to survive or function by suppressing, inhibiting, controlling, or reducing the pathogen and its metabolites.

There is rising interest in adopting biological control to combat plant infections from the standpoint of the microbiome. Using microbiome techniques in current worldwide breeding projects is another intriguing tactic [81]. The significance of plant pathogens and the interactions between the plant microbiome is increasingly being recognized, with a focus on pathogenic and mycotoxigenic *Fusarium* species [82]. *Fusarium* fungus can interact with the host microbiome at various phases of their life cycles and in diverse plant organs such as roots, stems, leaves, heads, and crop waste (Figure 2). *Fusarium* interacts with other fungi, bacteria, and *Fusarium* species. Recent research has produced a map of the cereal microbiome, revealing how several biotic and abiotic variables influence microbiome assembly [82].

Several research studies have examined naturally existing microorganisms in wheat for fusarium suppression. In a biotest with *F. graminearum* on wheat seedlings, Gdanetz and Trail 2017 [85] they identified endophytic fungi and bacteria that reduced disease severity. These strains included *Alternaria tenuissima* and *Alternaria* sp*., F. oxysporum, F. solani* and *Fusarium* sp*., Phoma sp., Penicillium reticulisporum* and *Penicillium commune.* In a different instance, 13 bacterial and fungal strains that belonged to the species *Bacillus amyloliquefaciens*, *Aureobasidium protae*, *Clonostachys rosea*, *Microdochium bolleyi*, *Phoma glomerata*, and *Sarocladium kiliense* were identified[86] and it has significantly reduced the *F. graminearum* disease on detached wheat spikelets, starting with 758 isolates.

Karlsson et al. 2017 [87] proposed mycoparasitism as the mode of action for a few fungal taxa, such as *Trichoderma* and *Clonostachys*. However, several bacterial antagonists [88], [89] and some fungal antagonists have been linked to the generation of antifungal secondary metabolites (antibiosis). Antagonistic interactions with *F. graminearum* have been linked to nutrient competition via iron-chelating siderophores [90]. Another example is utilizing biocontrol strains that metabolize choline, a substance found in wheat anthers that promotes *F. graminearum* hyphal development [91]. The relationship between a *Pseudomonas* strain and *F. graminearum* root infection in barley has been suggested to induce systemic resistance [92]. Despite the identification of numerous promising biocontrol agents against FHB, relatively few products have made it to market [54]. O'Callaghan 2016 [93]and Sundh and Eilenberg 2021 [94] suggest that inconsistent control effects in field situations, formulation issues, and time-consuming approval processes may contribute to this issue.



Source: Karlsson et al 2021 [82].

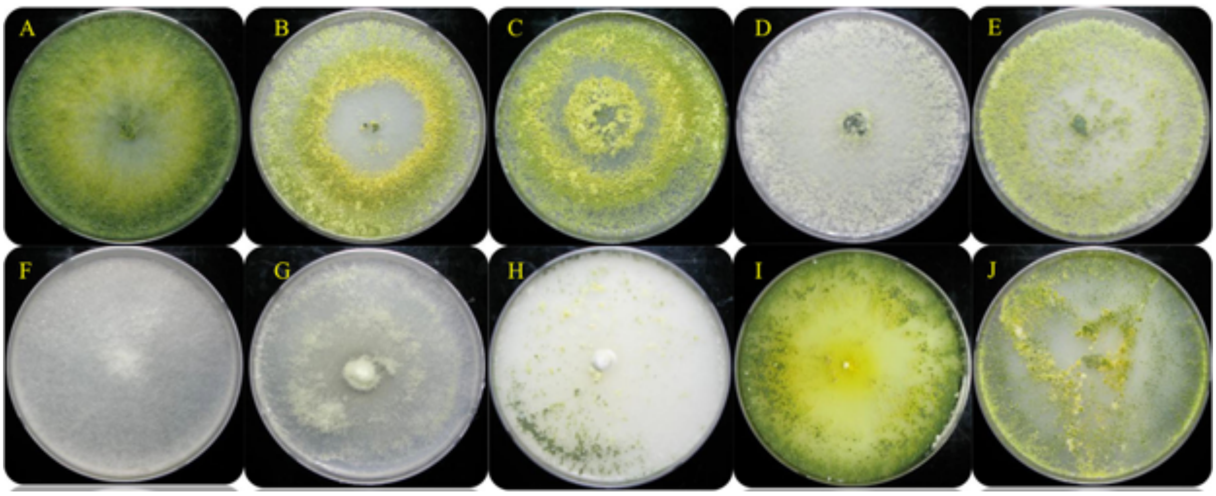
Fungal Biocontrol agents (Fungal BCAs)

There are various ways fungal BCAs and their fungal hosts interact as part of the biological control system. Vujanovic lists the following as examples of these interactions: mixed path interaction, which involves the release of antibiotics and lytic enzymes; direct interaction, which can involve mycoparasitism or hyperparasitism; and indirect interaction, which requires competition for nutrients or space and the induction of host resistance[95], [96]. It has been hypothesized that the most effective BCA will use a combination of these various interactions for pathogen control at any given time [53]. These interactions offer differing degrees of protection. BCAs are thought to be a more promising and eco-friendlier alternative to the chemical fungicides now in use, in addition to being more effective at protecting plants from plant diseases. Through mycoparasitism, antibiosis, and competition for nutrients and space, *Trichoderma* fungus, especially, contributes to the inhibition of *Fusarium* species complex pathogens growth and positively affects plant growth, especially the growth of their root systems, which is thought to be a favorable effect during drought periods [97].

Trichoderma

Trichoderma fungus is one of the many kinds of potential microorganisms that could be employed for both biological protection and the enhancement of cereal crop growth. These fungi have so far been utilized as commercial bio formulations for the biological control of phytopathogens (such as *Fusarium* spp.) primarily in the farming of vegetables, legumes, and oil plants [98], [99]. As of the present time, 375 species of *Trichoderma* are known to exist [100], [101]. According to Druzhinina et al. 2011 [100], these fungi are members of the Ascomycota division, Pezizomycotina subdivision, Sordariomycetes class, and Hypocreales order. These microorganisms can be parasites of other fungi and can be found in all climate zones in a variety of settings, such as decaying wood and bark. However, according to Rai et al. 2016 [102], they are primarily found in the soil. *Trichoderma* species fungi are easily isolated from soil, grow quickly in the lab, and produce many green and white conidia (Figure 3). *Trichoderma* species are some of the most active competitors of *Fusarium* fungi, exhibiting antagonistic tendencies against fungal infections that cause diseases in cereal crops [103]. For instance, mycoparasitism is the primary mechanism driving *Trichoderma* species' biocontrol [104]. Most published information on the use of *Trichoderma* fungus against *Fusarium* diseases came from research based on dual cultures that were conducted *in vitro* but few effective studies have been also reported at the plant level[97], [97], [105], [106], [107]. For instance, in a dual culture experiment conducted by Larran et al. 2020 [108], the *T. harzianum* strain demonstrated great promise for biocontrol of *F. sudanense*, a strain isolated from wheat grains, which causes seed rot and damping-off in wheat seedlings. This control was primarily based on mechanisms related to competition for nutrients or space. Microscopic analyses revealed that the direct methods (mycoparasitism) used by the *T. harzianum* strain to combat *Fusarium* species included penetration, plasmolysis, and curling. These findings imply that *T. harzianum* can release cellular enzymes that can penetrate and break down cell walls and cause plasmolysis, such as chitinases, proteases, and glucanases [108]. The test strains of *T. harzianum* in a dual culture with *F. graminearum* on potato dextrose agar [PDA], incubation in the dark at 25°C for 7 days) were also observed to be able to limit the growth of pathogenic mycelia by an average of 46%. Additionally, zones of inhibition were seen between colonies, which may indicate that the *Trichoderma* fungi produced specific metabolites (like antibiotics) to stop *F. graminearum* from growing.

Figure 3. *Colony appearance of the different selected* ***Trichoderma*** *spp. isolates on PDA (7 days). (A)* ***Trichoderma harzianum*** *KNU1; (B)* ***T. reesei*** *KNU4; (C)* ***T. harzianum*** *KNU10; (D)* ***T. harzianum*** *H22; (E)* ***T. atroviride*** *24; (F)* ***T. koningii*** *27; (G) T. virens 19; (H) T. longibrachiatum 28; (I) T. Pleuroticola P22; (J) T. asperellum 18.*



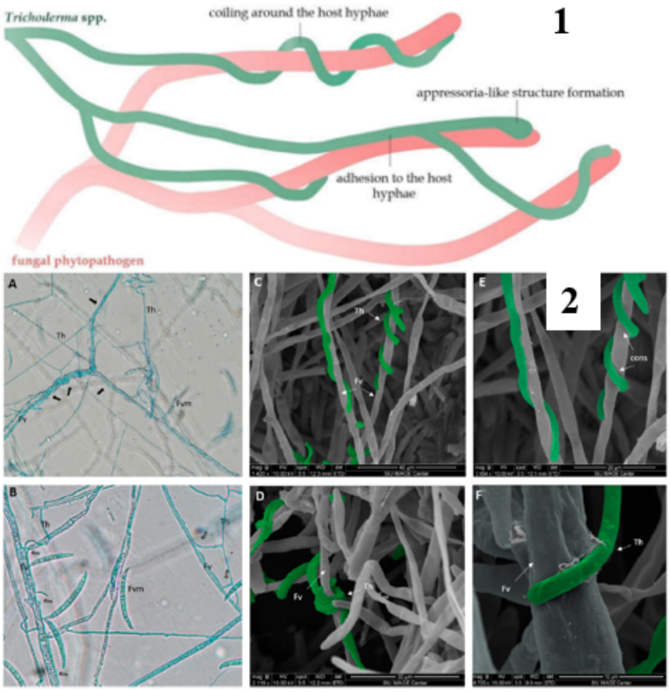
Source: Rai et al. 2016 [102]

Antagonistic Aspects of Trichoderma Fungi Against FGSC

Trichoderma species exhibit a wide range of antagonistic and bio-stimulating characteristics [107]. Several different processes, including mycoparasitism, antibiosis, and competition for nutrients and space, combine to give *Trichoderma* fungus its antagonistic characteristics [109]. Utilizing *Trichoderma* fungi to fighting the causal agents of Fusarium head blight in cereal crops appears to be a viable approach, given their diverse range of antagonistic characteristics demonstrated against FGSC diseases [110]. Moreover, it was shown by Matarese et al. 2012 [11], Xue et al. 2017 [111], and Tian et al. 2018 [112] that *T. asperellum*, *T. citrinoviride*, *T. gamsii*, *T. velutinum*, and *T. virens* effectively inhibited *F. graminearum* in wheat. According to Ferrigo et al. 2020 [113], *T. harzianum* exhibits antagonistic characteristics in maize crops against *F. verticillioides* and *F. graminearum*. Consequently, the biological protection of cereal crops should benefit from applying these *Trichoderma* strains.

Direct mycoparasitism, which consists of an antagonist breaking down the cell walls of the phytopathogen's mycelium and generating enzymes, is a highly significant phenomenon [104]. A rival recognizes phytopathogen hyphae and enlarges in their direction, releasing enzymes that break down cell walls. Subsequently, the antagonist coils around the phytopathogen's hyphae, inflicting mechanical harm and allowing its metabolites to enter, which ultimately results in the phytopathogen's death [114]. Figure 4A&B illustrates the mycoparasitism pathway of *Trichoderma* fungi.

Figure 4. *Schematic representation of mycoparasitic interaction:* ***(1)*** *mycoparasitic interaction of the* ***Trichoderma*** *hyphae with the hyphae of fungal pathogens.* ***(2)*** *Parasitism of* ***T. harzianum****. against* ***Fusarium*** *sp. observed under* ***2A and 2B****, light microscopy and* ***2C, 2D, 2E,*** *and* ***2F****, scanning electron microscopy.* ***A****, hyphae (Th) coiled around Fusarium sp. hyphae (Fv) (solid black arrows) at ×20 magnification;* ***B****, hyphae growing in parallel and closely associated with Fusarium sp. (empty black arrows) and* ***Fusarium*** *sp. macroconidia (Fvm), ×40 magnification;* ***C*** *and* ***D****, Fusarium sp. hyphae encoiled by the antagonist with hyphae penetration (hp);* ***E****, encoiling with greater magnification showing Fusarium sp. hyphal depression (hd) caused by Trichoderma in the coiling area; and* ***F,*** *beginning of coiling with apparent degradation of Fusarium sp. cell wall (dcw) in the interaction area.*



Source: Pimentel et al. 2020 [115]

Filaments of fungi are characterized by the presence of β-glucan and chitin in their cell walls. According to Tchameni et al. 2020 [116], lytic enzymes are essential for breaking down cell walls. As a result, *Trichoderma*'s high activity of enzymes like xylanases and cellulases helps it outcompete pathogenic fusarium fungi in the rhizosphere of cereal crops [117]. According to Loc et al. 2020 [118], *Trichoderma*'s antagonism of fungal infections is mediated in part by chitinases, glucanases, and proteases involved in mycoparasitism. Jaroszuk-Ściseł et al. 2019 [119] found that the *Trichoderma* strain's high chitinolytic and glucanolytic activity inhibited *Fusarium* growth in wheat by causing mycoparasitism and hyphae lysis. Thus, *Trichoderma* spp. can serve as biological fungicides, protecting plants from harmful fungus [120].

The antibiotic activities of *Trichoderma* spp. are also thought to be antagonistic. According to Saravanakumar et al. 2018 [121], antibiotics have antimicrobial effects on gram-positive bacteria as well as fungal infections that damage plants. *T. asperellum* produces trichotoxins, *T. harzianum* produces trichorzianins A and B, trichorzins HA and harzianins HB), *T. koningii* produces trichokonins, and *T. longibrachiatum* produces tricholongins BI/BII and longibrachins. These are some of the species that generate peptaibols[122].

Recent studies show that *Trichoderma* fungus can prevent the production of mycotoxins by antagonizing other fungi. Enzymes generated by *Trichoderma* spp. may also contribute to mycotoxin breakdown. Currently, the hunt for solutions to minimize mycotoxins in food is a global concern. Enzymes produced by *Trichoderma* fungi can modify mycotoxins, resulting in decreased toxicity compounds (e.g., DON-3G vs. DON or β-zearalenol [β-ZOL] vs. ZEN) [123], [124]. Thus, biological strategies, such as bioconversion of mycotoxins using microorganisms or enzymes, can provide an appealing alternative to chemical and physical techniques for mycotoxin reduction. Tian et al. 2020 [112] found that *T. asperellum*, *T. atroviride*, and *T. harzianum* inhibited the growth of *F. graminearum* mycelia in vitro, lowering pathogen production of ZEN and zearalanone (ZAN) by 93% and α-ZOL and β-ZOL by 80%, respectively. They proposed that one of the processes used by *Trichoderma* species to reduce ZEN toxicity is sulphation, which results in the synthesis of ZEN-14S and ZOL-14S [112], [125]. Furthermore, it has been shown, based on qualitative research, that *Trichoderma* fungi are capable of metabolizing DON biosynthesized by *F. graminearum* to deoxynivalenol-3-glucoside (DON-3G), a metabolite that is typically thought to be formed by plants detoxifying DON. This suggests that glycosylation-based detoxification is not limited to plants, as other research has demonstrated, but rather functions as a defense mechanism in *Trichoderma* fungus [112], [126]. Table 1 provides a comprehensive overview of the features of *Trichoderma* spp.'s capacity to convert mycotoxins made by *Fusarium* and other fungi.

Table 1*.Trichoderma spp. capable of degrading cereal mycotoxins or inhibiting their production under in vitro conditions*

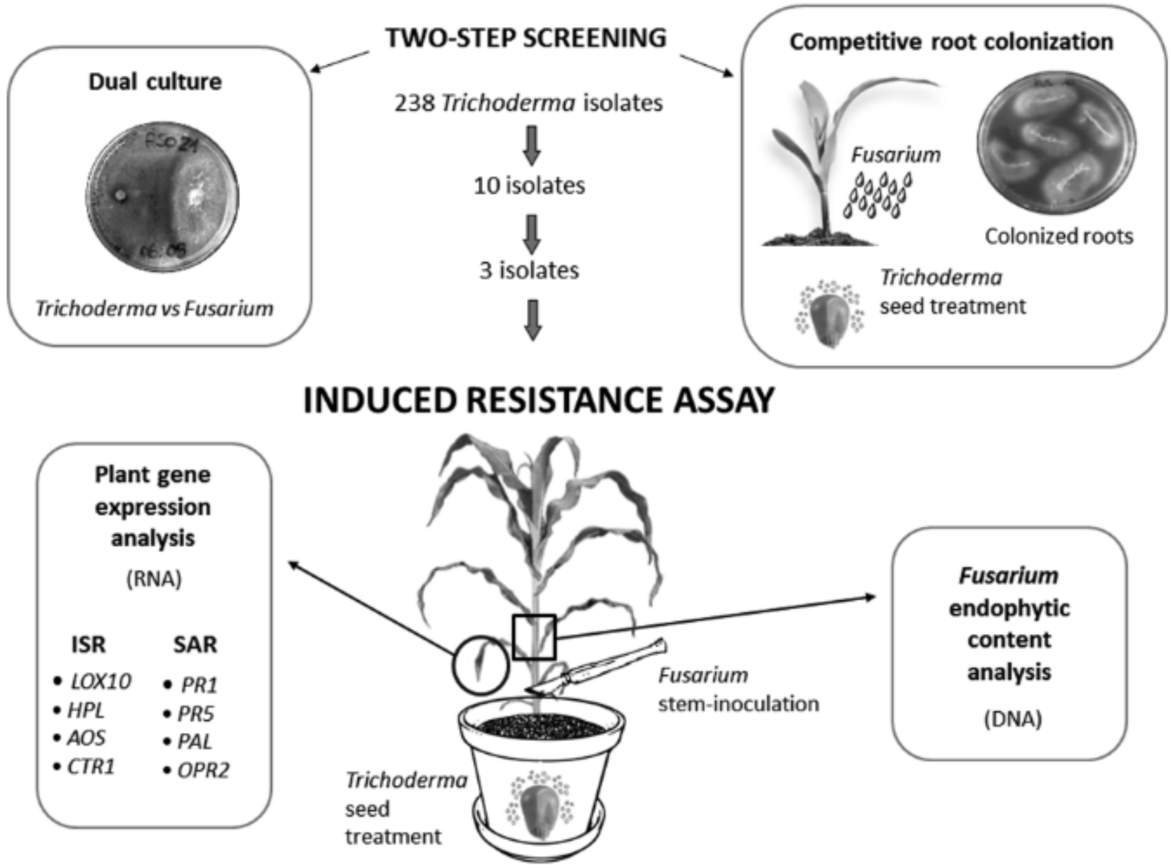
Trichoderma species	**Compound**	**Conditions of degradation**	**Degree of degradation (%)**	**Product**	**Reference**
T. asperellum, T. atroviride, T. harzianum	DON	25°C, PDA	20	DON-3G	[127]
T. asperellum, T. atroviride, T. harzianum, T. virens	ZEN	25°C, PDA	-	α-ZOL, β-ZOL, ZEN-14-sulphate	[112], [125]
T. koningii, T. longibranchiatum	ZEN	25°C, PDA	-	α-ZOL, ZEN-14-sulphate	[112], [125]
T. afroharzianum, T. gamsii	Fumonisin B1, B2, B3	25°C, PDA	≤50	-	[106]
T. harzianum	DON	25°C, greenhouse, on maize plants, 21 days	≤85	-	[113]
T. aggressivum	ZEN	25°C, liquid Czapek-Dox medium	≤90	-	[128]
T. asperellum	ZEN	25°C, PDA	-	ZOL-14-sulphate	[112]
T. gamsii, T. velutinum	DON	24°C, wheat, rice kernels	≤92	-	[11]

Abbreviations: DON, deoxynivalenol; DON- 3G, deoxynivalenol- 3- glucoside; PDA, potato dextrose agar; ZEN, zearalenone; ZOL, zearalenol.

Few *in vivo* investigations have evaluated the antagonistic properties of *Trichoderma* fungus against *Fusarium* species complex and their impact on plants. *T. harzianum* and *T. virens* can suppress the growth of *F. graminearum* in wheat crops planted in greenhouses or fields [129]. Foroutan 2013 [129] used *Trichoderma* species that had shown antagonism towards *F. graminearum* during *in vitro* studies in controlled conditions (a greenhouse where both *F. graminearum* and *T. harzianum/T. viride* inocula were added to the soil at a rate of 5 g/kg of soil) and in field conditions. The study revealed that the *Trichoderma* strains could reduce the frequency and severity of root and foot rot in wheat. Under greenhouse circumstances, the average disease incidence and severity decreased from 85% and 45%, respectively, in control (soil infested solely with the pathogen), to 14% and 8%, when the soil contained both the pathogen and one of the *T. harzianum* strains. Sarrocco et al. 2021 [130]looked into the possibility of using 10^5 conidia/ml of *T. gamsii* to control wheat fungal infection and demonstrated a considerable reduction in the pathogen's colonization of wheat straw by immersing straw pieces that had previously been infected with the pathogen in a solution designed to combat *F. graminearum.* The antagonistic relationship between *T. afroharzianum* and *F. culmorum* was examined by Bouanaka et al. 2021 [14]. Their findings showed that introducing a solution containing both *Trichoderma* and *F. culmorum* (*F. culmorum* 8×10^6 microconidia/ml and *T. afroharzianum* 8×10^8 spores/ml) during the flowering period helped to inhibit FHB by as much as 74.6% when compared to plants that were inoculated with *F. culmorum* spores alone. Ferrigo et al. 2020 [113] found that applying *T. harzianum* (10^5 spores/ml) to seeds reduced the prevalence of *Fusarium* ear rot (FER) in maize infected with *F. verticillioides* and *F. graminearum* by an average of 36% compared to plants from seeds not treated with *Trichoderma*. When the experiment was replicated in field trials under natural infection settings, DON buildup in the grain of plants treated with *Trichoderma* was reduced by 40% to 85% compared to plants treated with untreated seeds.*T. gamsii*, when applied to maize kernels, has been shown to induce systemic responses in the aerial portion of the plant, inhibiting the endophytic development of stem-inoculated *F. verticillioides* and modifying defense-related gene expression(Figure 5) [106].

It should be noted that *Trichoderma* is beneficial in controlling other diseases of cereal crops, even though FHB and FER pose the biggest risk to the cultivation of cereal crops. *In vivo,* treatment of *Bipolaris maydis* caused maize leaf disease was carried out using *T. viride,* and (0.5% spore suspension) was applied to the seeds, the percentage disease rate (diseases were graded on a scale of 1 to 5) was 58.9%; in contrast, the rate for seeds that were not treated with the study strains was 82.2% [131].

Figure 5. *Scheme of the study on induced resistanc. A preliminary two-step screening of a large collection of* ***Trichoderma*** *spp. isolates were carried out for antagonism (dual culture) and competition (competitive root colonization) towards* ***Fusarium verticillioides****. Then, an induced resistance assay was performed against* ***F. verticillioides*** *with three selected isolates, applied to kernels. The systemic effect on the endophytic development of the pathogen was evaluated by quantitative DNA analysis, and a gene expression study was carried out to elucidate the induced resistance pathways involved, based on specific defense-related marker genes.*

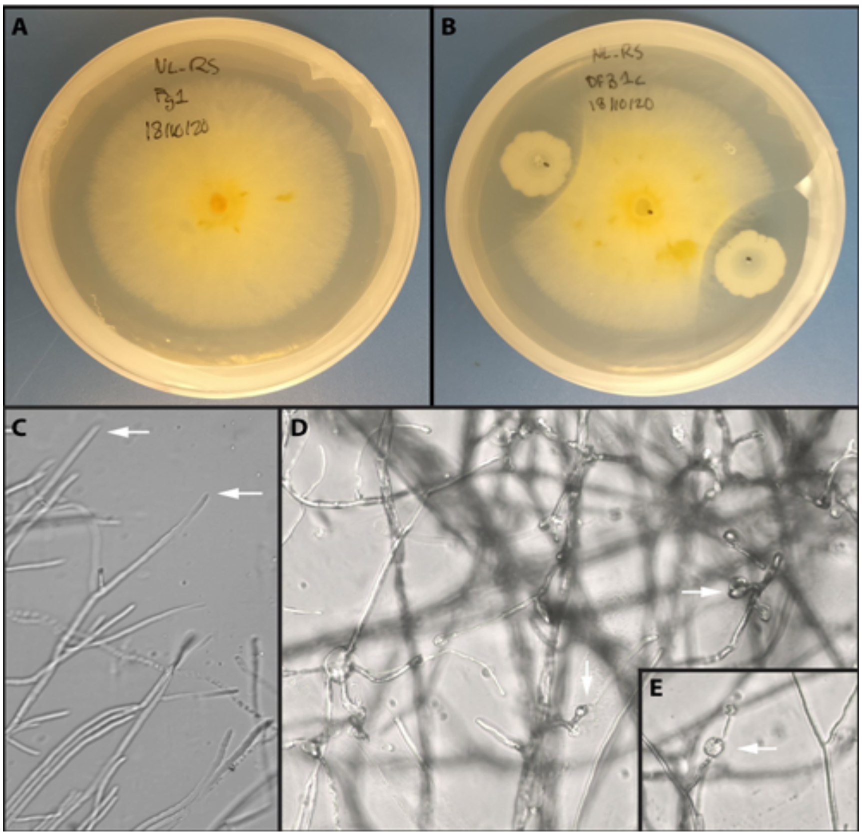


Source: Stefania et al. 2020 [106]

Bacterial Biocontrol Agents (Bacterial BCAs)

Bacterial BCAs have been shown in multiple trials to effectively reduce head blight, ear rot, and crown rot diseases of wheat caused by the *Fusarium* species complex, and several commercial solutions are now being developed. Several proven bacterial biological control mechanisms (antibiosis, competition, hyperparasitism, and induced resistance), can work together to control disease and, as a result, reduce mycotoxin contamination. It is also understood what the biological roles of some of the various mycotoxins produced by *Fusarium* species are, as well as how cereal enzymes or other fungi detoxify them and how bacterial BCAs can induce their breakdown [132], [133], [134].Plant growth-promoting rhizobacteria, or PGPR, is a type of microbial biocontrol that includes several bacterial isolates mostly obtained from the rhizosphere and can suppress plant diseases. Because they can use their antibiotic, competitive, or inducing plant defense response abilities against multiple plant pathogens on different host plants, isolates from the genera *Pseudomonas*, and *Bacillus* are the most studied bacteria that are developed as commercial BCAs [135], [136]. Recent work sheds light on the molecular mechanisms involved in the interaction between *Bacillus velezensis* and *F.graminearum* a biocontrol bacterium and a phytopathogenic fungus. They discovered the relationship between *B. velezensis* and *F.graminearum* by using a dual RNA-seq technique to examine transcriptional changes in both organisms (Figure 6). In dual culture, *B. velezensis* increased sporulation and phosphate stress while decreasing secondary metabolism, biofilm formation, and the tricarboxylic acid cycle. *F. graminearum* up-regulated genes encoding killer protein 4-like proteins and heavy metal resistance while down-regulating trichothecene production and phenol metabolism [132].

***Figure 6**. **Bacillus velezensis** E68 inhibits the growth of **Fusarium graminearum** DAOMC 180378 in dual culture. **(A)** **F. graminearum** DAOMC180378 grown in single culture on PDA, **(B)** Dual culture condition for **B. velezensis** E68 and **F. graminearum** DAOMC180378 on PDA. **(C)** Hyphal morphology of **F. graminearum** in a single culture. **(D)** and **(E)** Hyphal morphology of **F. graminearum** in dual culture with **B. velezensis**. Microscopy performed at 40x magnification.*



Source: Liang et al. 2023 [132]

Interactions Between Specific CerealCrop and Beneficial Microorganisms as A Promising Strategy to Combat FHB And FER Caused By FGSC

One viable tactic against FHB is the use of biocontrol agents in conjunction with cereal genotypes. This strategy entails using the natural interactions between certain wheat varieties and beneficial microbes to improve plant resilience and minimize disease incidence. For instance, research has demonstrated that *F. graminearum* infection in wheat can be successfully managed by the mycoparasitic biocontrol agent *Sphaerodes mycoparasitica*. This mycoparasite forms a symbiotic connection with the host plant, which helps to restrict the spread of the disease and prevent mycotoxin contamination. This biocontrol agent increased agronomic variables including spike quantity, spike weight, seed weight, plant biomass, and plant height when administered toward several wheat genotypes. It significantly decreased FHB symptoms[15], [137]. It is an effective next-generation BCA for managing FHB [138], [139]. Naranjo-Ortiz and Gabaldón [140] claim that it is one of the most well-researched mycoparasites in the Sordariomycetes [138], [139], [140], [141]. It is an excellent model system for researching polyphagous lifestyles and biotrophic mycoparasitism against various *Fusarium* species and related mycotoxins implicated in FHB [53]. Under current management tactics, there is a wide range of protocooperation between BCAs and crop genotypes, and OMICS (genomics-transcriptomics-proteomics) techniques hold promise for the discovery of novel protective mechanisms. Combining management measures results in more effective resistance to FHB, as demonstrated by the history of managing FHB in common and durum wheat and other cereal crops. Seed bio-priming is a cost-effective and environmentally friendly strategy that promotes the growth of beneficial microorganisms, leading to disease resistance and improved plant fitness in crops like wheat, maize, and rice [142], [143], [144], [145]. A recent study discovered that seed bacterial endophytes influenced barley seedling growth in a tissue-specific way, with some isolates affecting either root and/or shoot length. A few "high performing" bacterial isolates had dual functional activities, definitely boosting root and shoot length while also suppressing *F. graminearum* mycelium development *in vitro* [146]. *B. subtilis, B. licheniformis,* and *B. pumilis* were found in this work as novel seed bacterial endophytes that might be used as biocontrol to prevent the catastrophic scab disease on cereal crops and to promote development during seedling establishment. Another study indicated that *B. velezensis* (JCK-7158) effectively controls FHB in rice. JCK-7158 strain produces a variety of active antifungal compounds; nevertheless, its true disease control efficiency is due to the creation of plant systemic resistance. These findings suggest that JCK 7158 has the potential to be a new biocontrol agent for the treatment of FHB in rice plant genotypes [70].

Conclusion and Outlook

This paper embraces current developments in comprehending how pathogenic *Fusarium* species interact with fungal and bacterial BCAs in cereal crops. Promising results from utilizing these BCAs to control fusarium head blight caused by fusarium species complex on cereals have been shown, as well as evidence that, in some situations, they can minimize mycotoxin accumulation in grains. Beneficial bacterial and fungal BCAs, particularly, in *Bacillus* and *Trichoderma* genera widely used to mitigate disease caused by *Fusarium graminearum* and/or *Fusarium* species complex. These biocontrol agents compete for resources, produce antifungal molecules, and cause systemic resistance in plants, resulting in contributions as essential for achieving sustainable agriculture. Seed treatment with beneficial microbes before planting can improve seed germination, seedling vigor, and plant disease resistance [70], [147]. This method helps plants establish beneficial microbial cooperation earlier. A thorough strategy for treating *Fusarium* diseases can be achieved by combining biological management with other IDM techniques, such as crop rotation, resistant cultivars, and a decreased reliance on chemical fungicides [137]. Considering current management practices and shifting climatic conditions, it appears reasonable to make a more focused and intentional effort to investigate the areas of protocooperation between BCAs and resistant cereal crop genotypes in general. We now have a greater awareness that it makes sense to combine resistant cereal crop genotypes with biocontrol agents (BCAs) to promote protocooperation, particularly with the changing climate conditions around the globe. This strategy could improve overall sustainability, lessen reliance on chemical treatments, and increase crop resilience. To maximize their potential, future studies should examine in detail how these interactions adjust to shifting climates. Studies on new biocontrol agents, improving application techniques, and comprehending how biocontrol agents, the plant microbiome interact, and the development of FHB-resistant cereal genotypes are also highly appreciated. This will support the creation of long-lasting, more efficient, and feasible cereal crop fusarium disease management plans.

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Dual Leonardo Hibrit Sayılar

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Özet

Fibonacci sayıları ve genelleştirmeleri matematik, bilgisayar bilimi, kriptoloji, tıp, müzik gibi birçok bilim dalında uygulamalara sahiptir. Fibonacci sayıları başlangıç koşulları 0 ve 1 olmak üzere kendisinden önceki iki terimin toplanmasıyla elde edilir. Fibonacci benzeri sayı dizileri kullanılarak yeni hibrit sayıları tanımlamak son yıllarda ilgi çekici bir problemdir. Bu çalışmada ilk olarak, bileşenleri Leonardo ve Lucas-Leonardo sayılarından oluşan yeni bir dual hibrit sayı dizisi tanımlanacaktır. Daha sonra bu sayıların rekürans bağıntıları, üreteç fonksiyonları ve Binet formülleri elde edilerek çeşitli özellikleri elde edilecektir. Sonrasında bu yeni sayı dizisi ile Fibonacci ve Lucas sayıları arasındaki ilişki araştırılacaktır. Son olarak Vajda özdeşliği ve bazı temel sonuçların elde edilmesi amaçlanmaktadır.

Anahtar kelime : Dual hibrit sayıları, Leonardo sayıları, Lucas-Leonardo sayıları, Binet formülü, Üreteç fonksiyonu.

Giriş

Kompleks sayılar, dual sayılar ve hiperbolik sayılar fizikte, mekanikte, cebirsel geometride ve kinematikte birçok uygulama alanına sahiptir. Kompleks, dual ve hiperbolik sayı cümleleri sırasıyla aşağıdaki şekilde tanımlanır:

C =a0+a1i|a0,a1R,i2=-1,

D=a0+a1|a0,a1R, 2=0,ε≠0,

H=a0+a1h|a0,a1R, h2=1, h≠1.

2018 yılında Özdemir [1], dual sayılar, kompleks sayılar ve hiperbolik sayıları genelleştirmek amacıyla hibrit sayı sistemini tanımlanmıştır. Hibrit sayılar cümlesi,

K=a+bi+cϵ+dh:a,b,c,dR,i2=-1,2=0,h2=1

şeklinde tanımlanır. Burada i, ve h hibrit birimler olmak üzere ih=-hi=i+ϵeşitlikleri sağlanır.

Altınkaya vd. [2], hibrit sayı sisteminde katsayıları reel sayı almak yerine dual sayı alarak yeni bir sayı sistemi tanımlamışlardır ve bu sayıları dual hibrit sayılar olarak adlandırmışlardır. Seçgin vd. [3], bu sayıların geniş bir incelemesini yapmışlardır.

Dual hibrit sayılar cümlesi, dual birim ve i, , h hibrit birimler olmak üzere

DK:=a+bi+cϵ+dh:a,b,c,dD, i2=-1,2=0,h2=1

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şeklinde tanımlanır. Burada εi=iε, εϵ=ϵε ve εh=hε sağlanmaktadır. Dual hibrit sayılar cümlesi reel sayılar üzerinde 8-boyutlu değişmeli olmayan bir cebir teşkil eder ve bu cebirin bir bazı 1,i,,h,,εi,εϵ,εh dir. a=a1+a2, b=b1+b2, c=c1+c2, d=d1+d2ε∈D olmak üzere Q=a+bi+ϵ+dh∈DK dual hibrit sayısı

Q=a+bi+cϵ+dh=p+qε,

şeklinde ifade edilir.

Temel Kavramlar ve Tanımlar

Bu bölümde, çalışmanın sonraki bölümlerinde kullanılacak bazı tanımlar ve teoremler yer almaktadır.

Fibonacci dizisi {Fn}, başlangıç koşulları F0=0,F1=1 olmak üzere

Fn=Fn-1+Fn-2, n≥2 (2.1)

rekürans bağıntısı ile tanımlanır.

Benzer olarak Lucas dizisi de {Ln} başlangıç koşulları L0=2,L1=1 olmak üzere

Ln=Ln-1+Ln-2, n≥2 (2.2)

rekürans bağıntısı ile tanımlanır. Bu rekürans bağıntılarla ilişkilendirilen karakteristik denklem

t2-t-1=0

şeklindedir. Bu denklemi çözerek iki farklı karakteristik kök elde edilir:

=1+52 ve ϕ=1-52.

Fibonacci ve Lucas sayılarının Binet formülleri aşağıdaki gibidir:

Fn=n-nψ-ϕ, Ln=n+n (2.3)

Ayrıca şu eşitlikler de sağlanır:

2Fn+1=Fn+Ln+1, Ln=Fn-1+Fn+1, Ln=Fn+2-Fn-2. (2.4)

Fibonacci sayılarına benzer olarak tanımlanan Leonardo sayıları ilk olarak 1981 yılında Dijkstra [4] tarafından sıralama algoritmasında kullanılmıştır ve başlangıç koşulları L0=L1=1 olmak üzere

Ln=Ln-1+Ln-2+1, n≥2 (2.5)

rekürans bağıntısını sağlayan yeni bir sayı dizisi tanımlanılmıştır. Tamsayı dizileri elektronik ansiklopedisi OEIS'de [5] [A001595] numaralı dizi olarak yer almaktadır. Diğer yandan, Zhong vd. [6]. Lucas-Leonardo sayılarını başlangıç koşulları R0=3,R1=1 olmak üzere

Rn=Rn-1+Rn-2+1, n>1 (2.6)

şeklinde tanımlamışlardır. {Ln}, {Rn} dizileri aşağıdaki gibi üçüncü dereceden lineer rekürans bağıntısını sağlarlar:

Ln=2Ln-1-Ln-3, Rn=2Rn-1-Rn-3 (2.7)

, ve , (2.5-2.6) ile ilişkili karakteristik denklem t3-2t2+1=(t2-t-1)(t-1)=0 'ın kökleridir. Denklemi çözerek aşağıdaki gibi üç farklı kök elde edilir:

=1+52, ϕ=1-52, ω=1(2.8)

Bu kökler ile ilgili aşağıdakiler sağlanır:

ψ+ϕ+ω=2, ψ+ϕ=1, ψ-ϕ=5 (2.9)

ψϕ+ψω+ϕω=0

ψϕω=-1 veya ψϕ=-1

Ayrıca2+1=5, ψ2+1=-5, ϕ2+2=3, 2-2=5 ve 3+3=4 eşitlikler de geçerlidir. Öte yandan,

Ln=2(n+1-n+1)ψ-ϕ-1, (2.10)

Rn=2(n+n)-1 (2.11)

sırasıyla Leonardo ve Lucas-Leonardo dizilerinin Binet formülü olup, Fibonacci ve Lucas sayıları-nın Binet formüllerinden

Ln=2Fn+1-1 ve Rn=2Ln-1 (2.12)

eşitlikleri sağlanır. Ayrıca aşağıdaki ilişkiler de mevcuttur:

5Ln=2Ln+1+4Ln-5, Rn=2Ln-Ln-1 (2.13)

Şimdi dual Fibonacci ve Lucas hibrit sayılarını verebiliriz. Bu sayılar Szynal-Liana vd. [7] tarafından tanımlanmıştır. n-inci dual Fibonacci ve Lucas sayıları QFn=QFn-1+QFn-2, n≥2 QLn=QLn-1+QLn-2, n≥2 (2.14)

rekürans bağıntısını sağlarlar. Burada, sırasıyla, başlangıç koşulları

QF0=1+ε+1+2i+2+3ϵ+3+5h,

QF1=1+2ε+2+3i+3+5ϵ+5+8h,

QL0=2+ε+1+3i+3+4ϵ+4+7h,

QL1=1+3ε+3+4i+4+7ϵ+7+11h

ile verilir.

Catarina ve Borges [8]'da Leonardo sayılarının Binet formülünü ve üreteç fonksiyonunu elde etmişlerdir. Alp ve Koçer [9] ise Leonardo sayıları ile Fibonacci ve Lucas sayıları arasındaki ilişkileri inceleyip, özdeşlikler elde etmiştir. Soykan [10] çalışmasında Leonardo sayılarının bir genellemesini tanımlamış ve genelleştirilmiş Leonardo sayılarının bazı özelliklerini vermiştir. Ayrıca Seçgin [11] kendi makalesinde Leonardo, Leonardo-Lucas ve Modified Leonardo eliptik quaternionları tanımlayıp bazı özellikleini inceledikten sonra matris temsillerini vermiştir.

Dual Leonardo ve Lucas-Leonardo Hibrit Sayıları

Bu bölümde, öncelikle dual Leonardo ve Lucas-Leonardo sayı dizilerini verip ardından dual Leonardo ve Lucas-Leonardo hibrit sayı dizilerini ve bu dizilerin temel özellikleri incelenmiştir.

Tanım 3.1 n≥2 için n-inci dual Leonardo ve Lucas-Leonardo hibrit sayıları sırasıyla

QLn=DLn+DLn+1i+DLn+2ϵ+DLn+3h (3.1)

QRn=DRn+DRn+1i+DRn+2ϵ+DRn+3h (3.2)

şeklindedir. Burada, DL_n ve DR_n, sırasıyla, n-inci dual Leonardo, Lucas-Leonardo sayılarıdır [12]. Ayrıca, $\{QL_n\}$ ve $\{QR_n\}$ dizileri sırasıyla

$$QL_n=2QL_{n-1}-QL_{n-3}, \quad (3.3)$$

$$QR1,n=2QR_{n-1}-QR_{n-3},$$

üçüncü dereceden lineer rekürans bağıntısını sağlarlar.

Tanım 3.2 Dual Leonardo hibrit sayılarının cümlesi

$$DKL_n=QL_n=DL_n+DL_{n+1}i+DL_{n+2}\epsilon+DL_{n+3}: \text{ i,,h hibrit birimlerdir}$$

şeklinde tanımlanır ve ayrıca dual birim olmak üzere bir dual Leonardo hibrit sayısı

$$DL_n=L_n+L_{n+1}$$

şeklinde de ifade edilir.

Dual Lucas-Leonardo hibrit sayılarının cümlesi

$$DKR_n=QR_n=DR_n+DR_{n+1}i+DR_{n+2}\epsilon+DR_{n+3}: \text{ i,,hhibrit birim lerdir}$$

şeklinde tanımlanır ve ayrıca dual birim olmak üzere bir dual Lucas-Leonardo hibrit sayısı

$$DR_n=R_n+R_{n+1}$$

şeklinde de ifade edilir.

Teorem 3.3 Dual Leonardo ve Lucas-Leonardo hibrit sayılarının üreteç fonksiyonları

$$GFQL_n(t)=QL_0+(QL_1-2QL_0)t+(QL_2-2QL_1)t2t3-2t+1 \quad (3.4)$$

$$GFQR_n(t)=QR_0+(QR_1-2QR_0)t+(QR_2-2QR_1)t2t3-2t+1$$

şeklindedir.

İspat. QL_n dual Leonardo hibrit sayısının üreteç fonksiyonu

$$GFQL_n(t)=QL_0+QL_1t+LQ_2t^2+\ldots+QL_nt^n+\ldots \quad (3.5)$$

olsun. Bu eşitliğin her iki tarafı $-2t$ ve t^3 ile çarpıldığında,

$$-2tGFQL_n(t)=-2QL_0t-2QL_1t^2-2QL_2t^3-\ldots-2QL_nt^{n+1}+\ldots$$

$$t^3GFQL_nt=QL_0t^3+QL_1t^4+QL_2t^5+\ldots+QL_nt^{n+3}+\ldots$$

elde edilirler. Dual Leonardo hibrit sayılarının başlangıç koşulları da kullanılarak ve gerekli işlemler yapılarak (3.4) elde edilir. Dual Lucas-Leonardo hibrit sayının üreteç fonksiyonu da benzer şekilde bulunur.

Sonuç 3.4 (2.12) ve (2.14)'i göz önüne alındığında, aşağıdaki sonuçlar elde edilir.

$$DL_n=L_n+L_{n+1}=2F_{n+1}-1+(2F_{n+2}-1)$$

$$=2(F_{n+1}+F_{n+2})(1+\varepsilon)$$

$$=2DF_{n+1}-,$$

$$5DL_n=2L_{n+1}+4L_{n+1}-5+(2L_{n+2}+4L_{n+1}-5)$$

=2(Ln+1+Ln+2)+4(Ln+Ln+1)-5

=2DLn+1+4DLn-5,

DRn=2Ln-Ln-1=2Ln-Ln-1+(2Ln+1-Ln)

=2(Ln+Ln+1)-(Ln-1+Ln)

=2DLn-DLn-1,

DRn=Rn+Rn+1=2Ln-1+(2Ln+1-1)

=2(Ln+Ln+1)-(1+ε)

=2DLn-.

Teorem 3.5 Dual Leonardo ve Lucas-Leonardo hibrit sayılarının Binet formülleri

QLn=2(n+1*-n+1*)ψ-ϕ-Q*, (3.6)

QLn=2(n*+n*)-Q* (3.7)

şeklindedir. Burada *=1+ψi+2ϵ+3h, *=1+ϕi+2ϵ+3h ve Q*=1+i+ϵ+h, =1+ψε, =1+ϕε ve =1+ε dır.

İspat. Leonardo sayılarına ait Binet formülü (2.12)-(2.14)'de verilmiştir. Öncelikle Dual Leonardo ve Lucas-Leonardo sayılarının binet formülünü bulalım.

DLn =Ln+Ln+1

=2(n+1-n+1)ψ-ϕ-1+(2(n+1-n+1)ψ-ϕ-1)

=2(n+1(1+ψε)ψ-ϕ-2(n+1(1+ϕε)ψ-ϕ-(1+ε)

=2n+1ψ-ϕ-2n+1ψ-ϕ-, (3.8)

DRn=Rn+Rn+1

=2(n+n)-1+(2(n+n)-1)

=2n(1+ψ)+2n(1+ϕ)-(1+ε)

=2n+2n- (3.9)

(3.1) ve (3.8)'i göz önünde bulundurulduğunda,

QLn=DLn+DLn+1i+DLn+2ϵ+Ln+3h

=2(n+1-n+1)ψ-ϕ-+(2(n+2-n+2)ψ-ϕ-)i

+(2(n+3-n+3)ψ-ϕ-)ϵ+(2(n+4-n+4)ψ-ϕ-)h

=2n+1ψ-ϕ1+ψi+2ϵ+3h-2n+1ψ-ϕ1+ϕi+2ϵ+3h

-(1+i+ϵ+h)

=2n+1*-2n+1*ψ-ϕ-Q*

elde edilir.

(3.2) ve(3.9)'i göz önünde bulundurulduğunda, QRn=DRn+DRn+1i+DRn+2ϵ+DRn+3h

=2(n+n)-+(2(n+1+n+1)-)i

+(2(n+2+n+2)-)ϵ+(2(n+3+n+3)-)h

=2n1+ψi+2ϵ+3h+2n1+ϕi+2ϵ+3h

-(1+i+ϵ+h)

=2n*+n*-Q*

elde edilir.

Teorem 3.6 Dual Leonardo hibrit sayısı için Vajda özdeşliği

QLn+s-QLnQLn+r+s=255(2(-1)n+1Fr(s**-s**)

+n+1(1-r)(1+(2)(*Q*-sQ**)

-n+1(1-r)(1+2)(*Q*-sQ**))

şeklindedir. Burada Fr, r-inci Fibonacci sayısıdır.

İspat. VL=QLn+s-QLnQLn+r+s olmak üzere dual Leonardo hibrit sayısı için Binet formülünü kullanılarak

VL=QLn+rQLn+s-QLnQLnLn+r+s

=2n+r+1*-2n+r+1*ψ-ϕ-Q*2n+s+1*-2n+s+1*ψ-ϕ-Q*

-2n+1*-2n+1*ψ-ϕ-Q*2n+r+s+1*-2n+r+s+1*ψ-ϕ-Q*

=4(ψ-ϕ)2(2n+r+s+2(*)2()2-n+r+1n+s+1**

-n+r+1n+s+1**-2n+r+s+2(*)2()2)

-2(ψ-ϕ)n+r+1*Q*-n+r+1*Q*+n+s+1Q**-n+r+1Q**

-4(ψ-ϕ)2(2n+r+s+2(*)2()2-n+1n+r+s+1**

-n+1n+r+s+1**+2n+r+s+2(*)2()2)

+2(ψ-ϕ)n+1*Q*n+1*Q*+n+r+s+1Q**-n+r+s+1Q**

=4(ψ-ϕ)2n+1n+s+1(r-r)**+n+1n+s+1(r-r)**

+2ψ-ϕ(n+1(1-r)*Q*+n+1(r-1)*Q*

-n+s+1(1-r)Q**-n+s+1(r-1)Q***)

=4(ψ-ϕ)2n+1n+1(r-r)(s**-s**)

+2ψ-ϕ(n+1(1-r)(*Q*-sQ**)-n+1(1-r)(*Q*sQ**)

=455(-1)n+1Fr(s**-s**)

+255n+1(1-r)((*Q*-sQ**)-n+1(1-r)(*Q*-sQ**) elde edilir.

Sonuç 3.7 Teorem 3.6'daki eşitlikte r,s⟶m ve n⟶n-m olarak alındığında n ve m negatif olmayan tamsayılar ve n≥m olmak üzere, dual Leonardo hibrit sayısı için Catalan özdeşliği

QLn-sQLn+s-QLn2=255(2(-1)n+1F-s(s**-s**)

+n+1(1--s)(*Q*-sQ**

-n+1(1--s)(*Q*-sQ**))

olarak bulunur.

Sonuç 3.8 n negatif olmayan bir tamsayı olmak üzere, Sonuç 3.7'deki eşitlikte s=1 alındığında dual Leonardo hibrit sayısı için Cassini özdeşliği

QLn-1QLn+1-QLn2=255(2(-1)n+1(**-ϕ**)

+n+1(1--1)(*Q*-ψQ**)

-n+1(1--1)(*Q*-ϕQ**)

olarak bulunur.

Sonuç 3.9 Teorem 3.6'daki eşitlikte s⟶m-n, ve r=1 alındığında n ve m negatif olmayan tamsayılar ve m≥n olmak üzere, dual Leonardo hibrit sayısı için d'Ocagne özdeşliği

QLn-1QLn-QLnQLm+1=255(2(-1)n+1(m-n**-m-n**)

+n+1(1-ψ)(*Q*-m-nQ**)

-n+1(1-ϕ)(*Q*-m-nQ**)

olarak bulunur.

Teorem 3.10 Dual Lucas-Leonardo hibrit sayısı için Vajda özdeşliği

QRn+rQRn+s-QRnRn+r+s=45(-1)nFr(s**-s**)

+n(r-1)(*Q*-sQ**)

-n(r-1)(*Q*-sQ**)

şeklindedir. Burada Fr, r-inci Fibonacci sayısıdır.

İspat. VRn=QRn+rQRn+s-QRnQRn+r+s olmak üzere dual Leonardo hibrit sayısı için Binet formülünü kullanılarak

VRn=QRn+rQRn+s-QRnQRn+r+s

=(2(n+r*+n+r*)-Q*)(2(n+s*+n+s*)-Q*)

-(2(n*+n*)-Q*)(2(n+r+s*+n+r+s*)-Q*)

=4(n+rn+s-nn+r+s)**)+4(n+rn+s-nn+r+s)**

+2(n-n+r)*Q*+2(nn+r)*Q*

+2(n+r+s-n+s)Q**+2(n+r+sn+s)Q**

=4(ψϕ)nsFr(r-r))**+4(ψϕ)nsFr(r-r))**

+n(r-1)(*Q*-sQ**)+n(r-1)(*Q*-sQ**)

=45(-1)nFr(s**-s**)+n(r-1)(*Q*-sQ**)

+n(r-1)(*Q*-sQ**)

elde edilir.

Sonuç 3.11 Teorem 3.10'daki eşitlikte r,s⟶m ve n⟶n-m olarak alındığında n ve m negatif olmayan tamsayılar ve n≥m olmak üzere, dual Lucas-Leonardo hibrit sayısı için Catalan özdeşliği

QRn-sQRn+s-QRn2=45(-1)nF-s(s**-s**)

+n-s-1*Q*-sQ**

+n(-s-1)(*Q*-sQ**)

olarak bulunur.

Sonuç 3.12 n negatif olmayan bir tamsayı olmak üzere, Sonuç 3.11'deki eşitlikte s=1 alındığında dual Lucas-Leonardo hibrit sayısı için Cassini özdeşliği

QRn-1QRn+1-QRn2=45(-1)n(**-ψ**)

+n-1-1*Q*-ψQ**

+n(-1-1)(*Q*-ϕQ**)

olarak bulunur.

Sonuç 3.13 Teorem 3.10'daki eşitlikte s⟶m-n, ve r=1 alındığında n ve m negatif olmayan tamsayılar ve m≥n olmak üzere, dual Lucas-Leonardo hibrit sayısı için d'Ocagne özdeşliği

QRn+1QRm-QRnQRm+1=45(-1)n(m-n**-s**)

+n(ψ-1)(*Q*-m-1Q**)

+n(ϕ-1)(*Q*-m-nQ**)

olarak bulunur.

Sonuç

Bu çalışmada, dual Leonardo ve Lucas-Leonardo hibrit sayıları tanınlanmıştır. Dual Leonardo ve Lucas-Leonardo hibrit sayılarının Fibonacci ve Lucas sayılarıyla ilişkisi verilmiştir. Bu sayıların temel özellikleri, Binet formülü, üreteç fonksiyonu ve bazı özdeşlikleri incelenmiştir. Ayrıca, bu iki yeni sayı için Vajda özdeşli bulunmuştur ve dolasıyla Vajda özdeşliğinin bazı indirgemelerine sonuç olarak yer verilmiştir.

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