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Potential and Application of Pteridophytes as Ecological Bioindicators: An Updated Review

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Abstract— Pteridophytes are essential as bioindicators in environmental quality monitoring and assessment due to their sensitivity to various air, water and soil pollutants. This study aims to review the recent literature on using ferns as bioindicators, focusing on the methodologies applied and results obtained from various case studies. The research method used in this review involved a systematic literature search through reputable scientific databases such as PubMed, Google Scholar, and Web of Science, with related keywords such as "ferns," "bioindicators," "air pollution," "water pollution," and "heavy metals." The studies analysed showed that ferns such as Pteridium aquilinum, Polystichum setiferum, Adiantum capillus-veneris, and Azolla filiculoides are effective in detecting air pollutants such as sulphur dioxide (SO_2) and nitrogen dioxide (NO_2), as well as heavy metals in water and soil. Research methodologies reported in the literature involve measuring physiological and biochemical parameters, such as chlorophyll content, antioxidant enzyme activity, and analysis of heavy metal content, which provide accurate data on the impact of pollution on ecosystems. Stable isotope analyses have also helped trace pollutant sources and understand complex biogeochemical dynamics in various ecosystems. Results from the review show that ferns have a high sensitivity to pollutants, making them a reliable tool for environmental monitoring. In addition, using molecular techniques such as eDNA enables the identification of microorganism species associated with ferns, providing additional insights into ecosystem health and pollution impacts. The learnings from this case study underline the importance of multidisciplinary approaches and long-term monitoring in bioindicator research. The findings may help develop more effective and sustainable environmental monitoring strategies.

Keywords: Air pollutans, soil pollutants, Sulphur dioxide, Nitrogen dioxide, water pollutans

I. INTRODUCTION

Pteridophytes are a group of plants that have existed since prehistoric times and have significant ecological roles in various ecosystems [1]. They are often found in multiple habitats, ranging from tropical rainforests to humid mountainous regions, and are known for their ability to survive in extreme environmental conditions [2]. One aspect that is increasingly attracting the attention of scientists is the potential of ferns as bioindicators in ecological studies [3]. Bioindicators are organisms used to monitor the environment's health, as changes in the presence, condition, or behaviour of ferns can reflect the quality of the environment in which they live [4]. In this context, ferns offer unique advantages that make them ideal subjects for bioindicator research [5]. The potential of ferns as bioindicators lies in their sensitivity to environmental changes, especially to air, water and soil pollution [6]. For example, some fern species respond rapidly to air pollutants such as sulphur dioxide and ozone, which can cause measurable physiological changes in these plants [7]. In addition, ferns can also accumulate heavy metals in fern tissues, making them effective indicators of soil and water pollution [8]. This ability is invaluable in environmental monitoring and ecosystem management, especially in areas prone to environmental degradation due to human activities such as mining, industrialisation and urbanisation [9].

In recent decades, research on using ferns as bioindicators has proliferated. These studies show that ferns can indicate the presence of pollutants and provide information on the extent and source of pollution [10]. For example, analyses of stable isotopes in fern tissues can help trace the source of pollution. In contrast, studies on fern community diversity can provide insights into the long-term impacts of climate change and land use [11]. In addition, molecular approaches such as environmental DNA (eDNA) analysis have begun to be applied to study the microbial communities associated with ferns, paving the way for a deeper understanding of ecological interactions and responses to environmental stress [2]. Practical applications of using ferns as bioindicators cover a wide range of fields, including air and water quality monitoring, soil pollution detection, and evaluation of overall ecosystem health [13]. In protected forest areas and national parks, ferns can be used to assess the impact of tourism activities and climate change [14]. In urban areas, they can help monitor air pollution and provide essential data for better air quality management [15]. In agriculture, ferns can detect soil contamination by pesticides and heavy metals, essential for food safety and agricultural sustainability [16].

Overall, the potential and applications of ferns as ecological bioindicators offer a powerful and versatile tool for environmental research and management. This recent review aims to summarise the current findings in this field, evaluate the methods used, and identify opportunities and challenges in their practical application [17]. With a better understanding of the role of ferns as bioindicators, we can improve ecosystem conservation and restoration efforts and develop more effective strategies to maintain environmental health in the future [18].

II. Methods

This study used a systematic review approach to evaluate and summarise the scientific literature on the potential and application of ferns as ecological bioindicators. This approach was chosen to provide a comprehensive overview of recent findings, research trends, and methods used in these studies [18]. Inclusion criteria included articles published in peer-reviewed scientific journals between 2013 and 2023, which addressed ferns as bioindicators for air, water, or soil pollution and used experimental, observational, or ecological modelling methods [19]. Articles irrelevant to the topic, not available in English or Indonesian, or reports or opinion articles not based on scientific research were excluded [4]. Literature searches were conducted through major scientific databases such as PubMed, Web of Science, Scopus, Google Scholar, and SpringerLink [5]. The keywords used included "ferns as bioindicators," "Pteridophyta ecological monitoring," "ferns pollution indicators," "ferns environmental assessment," and "bioindicator species water soil pollution" [20]. The search procedure included identifying relevant articles, screening abstracts and titles, selecting articles based on inclusion and exclusion criteria, extracting relevant data, and assessing study quality using a critical appraisal tool [8].

The extracted data were qualitatively analysed using a narrative approach to identify key themes, trends and gaps in the research [9]. This analysis included a description of the methodology, synthesis of findings, and identification of research gaps to offer recommendations for future research [10]. The results were validated by triangulating data from different sources and using analysis methods, as well as consulting with experts in the field of ecology and bioindicators [21]. The review results were reported systematically to contribute significantly to understanding the role and application of ferns as ecological bioindicators and to guide future studies [22].

III. Results And Discussion

3.1. Diversity of Pteridophytes as Bioindicators

Pteridophyte species diversity is essential to ecosystem function and as an environmental bioindicator. Diverse fern species exhibit varying degrees of sensitivity to environmental factors such as air, soil, and water pollution, which makes ferns a valuable tool for monitoring ecosystem conditions [19]. These diversity analyses provide important insights into ecosystem health and the impacts of human activities. The diversity of ferns in tropical rainforests is very high, with hundreds of species that have unique adaptations to specific environmental conditions [23]. These species can provide information on fern habitat quality through changes in fern distribution and abundance [10]. For example, some fern species that are highly sensitive to pollution can serve as early indicators of environmental degradation. In contrast, more tolerant species can indicate areas with suitable environmental conditions [11].

In mountainous areas, the diversity of species of ferns is also significant, with many species found only at certain altitudes and strongly influenced by climate change. Research by [24] revealed that variations in fern species diversity in these areas can be used to monitor the impacts of climate change and human activities such as logging and infrastructure development. Species sensitive to temperature and humidity changes may indicate broader environmental changes [13]. In urban ecosystems, fern species diversity also shows exciting patterns. Species such as *Pteris vittata* and *Adiantum capillus-veneris* are often found in areas contaminated by heavy metal pollutants, demonstrating the ability of ferns to survive and even help mitigate pollution [25]. The diversity of species of ferns in urban areas can provide important information on pollution levels and aid in better environmental management planning [26]. Overall, the distribution and diversity of fern species as bioindicators provide a powerful tool for monitoring and evaluating ecosystem health. By understanding how fern species respond to various environmental conditions, we can gain valuable insights into ecosystem change and the impacts of human activities and develop more effective strategies for environmental conservation and restoration [17].

3.2. Pteridophytes Sensitivity to Pollutants

Pteridophytes have a high sensitivity to air pollutants, such as sulfur dioxide (SO_2) and ozone (O_3), making them effective bioindicators of air quality. Sulphur dioxide is a significant pollutant from fossil fuel combustion and industrial activities. Research shows that exposure to SO_2 causes damage to the leaves of ferns, inhibits photosynthesis, and reduces plant growth [1]. For example, species such as Pteridium aquilinum show symptoms of leaf necrosis when exposed to high concentrations of SO_2 [19]. These effects reflect poor air quality and indicate the source of pollution and potential impacts on the surrounding ecosystem [27]. Ozone, formed from photochemical reactions between nitrogen oxides and volatile organic compounds, is also known to damage ferns. Research by [28] showed that species such as *Polystichum munitum* experienced decreased photosynthesis and cellular damage to leaves when exposed to ozone. This physiological response makes ferns a sensitive indicator of ozone levels in the fern environment. In addition, field observations in various ecosystems show that ferns growing in areas with high ozone concentrations often show signs of oxidative stress, which can be used to monitor and assess air quality [8].

Ferns are also widely used to detect pollution in water bodies, hefty metals and excess nutrients. Heavy metals such as cadmium, lead, and mercury can accumulate in fern tissues, making ferns an effective bioindicator of water contamination [10]. Species such as *Azolla filiculoides* and *Salvinia natans* have been intensively studied for their ability to absorb and accumulate heavy metals from water [23]. Studies by [24] showed that Azolla filiculoides can accumulate cadmium in fern tissues to very high concentrations, making it an effective tool to detect and mitigate heavy metal pollution in water bodies. In addition to heavy metals, ferns are also used to detect excess nutrients, such as nitrogen and phosphorus, that often cause eutrophication in water bodies. Species such as *Ceratopteris thalictroides* show a significant increase in biomass when exposed to high concentrations of nitrogen and phosphorus, which can be used as an indicator of nutrient pollution [29]. Using ferns in water quality monitoring also includes bioaccumulation techniques, where the concentration of pollutants in plant tissues is measured to give an idea of the level and type of pollution in the water environment [16].

The ability of ferns to accumulate heavy metals and other pollutants from soil makes them important bioindicators of soil pollution. Heavy metals such as arsenic, lead and cadmium are often found in soils contaminated by industrial and agricultural activities. Ferns such as *Pteris vittata*, known as arsenic hyperaccumulators, can absorb arsenic from soil in high concentrations without showing significant signs of toxicity [30]. Research by [33] suggests that *Pteris vittata* can be used in phytoremediation, a process in which plants are used to remove, stabilise, or detoxify pollutants from soil. Besides arsenic, ferns are also effective in accumulating lead and cadmium from polluted soil. Species such as *Pteridium aquilinum* and *Athyrium yokoscense* have demonstrated the ability to sequester lead from polluted soil, making ferns ideal for use in contaminated soil remediation [32]. Monitoring techniques using ferns involve measuring heavy metal concentrations in plant tissues to assess the extent of soil contamination [26]. The successful use of ferns as bioindicators of soil pollution also depends on understanding the complex interactions between plants, soil, and pollutants, as well as the specific adaptations of different fern species to different environmental conditions [20]. Overall, the sensitivity of ferns to air, water and soil pollution makes them a handy tool in environmental monitoring and ecosystem quality assessment. The ability of ferns to respond to specific pollutants and accumulate contaminants makes ferns not only an effective indicator but also a potential agent in environmental remediation strategies. With further research and the development of new methods, ferns may play an increasingly important role in environmental management and protection in the future [17].

3.3. A method for using pteridophytes as bioindicators

1. The Experimental Method

In experimental research to measure ferns' physiological and biochemical responses to pollution, various techniques and methods are used to obtain accurate and reliable data. One of the main methods is monitoring physiological changes in the leaves and roots of ferns when exposed to certain pollutants. Research by [1] showed that sulfur dioxide (SO_2) exposure in ferns can cause significant changes in photosynthetic activity, measured through decreased chlorophyll levels and increased oxidative stress in leaves. In addition, parameters such as transpiration rate, biomass growth, and relative water content are often measured to assess the effects of air pollution on ferns [19]. Another technique used is biochemical analysis, which measures antioxidant enzymes such as catalase, peroxidase, and superoxide dismutase. Research by [28] found that increased activity of these enzymes in Polystichum munitum species indicated oxidative stress due to ozone exposure. This method provides in-depth information on plant defence mechanisms against air pollutants and helps identify the most sensitive and resistant species to pollution [8]. Experiments also often involve the analysis of heavy metal content in fern tissues to assess the extent of accumulation of pollutants from soil and water. Techniques such as atomic absorption spectrometry (AAS) and inductively coupled plasma mass spectrometry (ICP-MS) are used to measure heavy metal concentrations in plant tissue samples [10]. Research by [24] showed that species such as Azolla filiculoides can accumulate high concentrations of cadmium and lead, making it an effective tool for detecting and mitigating environmental heavy metal pollution.

2. Stable Isotope Analyses

Stable isotope analysis has become an increasingly important tool in environmental research, particularly for tracking the sources and extent of pollution. Stable isotopes are variants of chemical elements with different numbers of neutrons but are not radioactive. Using ferns as bioindicators, stable isotope analysis can help identify pollutant sources and understand complex environmental dynamics [23]. Stable isotopes of nitrogen (^{15}N) and carbon (^{13}C) are often used to trace the origins of nutrient pollution and assess ecosystem interactions. Research by [31] showed that nitrogen isotope analyses in fern tissues can reveal sources of nitrogen pollution, such as agricultural runoff or industrial emissions. Species such as Ceratopteris thalictroides have been used to measure nitrogen isotope variation in freshwater habitats, showing significant differences between contaminated and non-contaminated areas [25]. In addition, carbon isotope analysis can be used to understand the contribution of carbon pollution from anthropogenic and natural sources. Research by [31] found that carbon isotope variations in fern leaves can be used to monitor changes in ecosystem carbon inputs due to deforestation and land use change. By analysing carbon and nitrogen isotope ratios in fern tissues, researchers can gain a clearer picture of the biogeochemical processes that influence the distribution of pollutants in the environment [30].

3. Molecular Approach (eDNA)

Molecular approaches, particularly environmental DNA (eDNA) analysis, have opened new avenues in ecological research and environmental monitoring. eDNA refers to DNA fragments released by organisms into the environment, which can be extracted and analysed to identify the presence of specific species and microbial communities associated with ferns [26]. In the context of using ferns as bioindicators, eDNA can be used to identify microorganisms associated with the roots and leaves of ferns, which can provide indications about environmental conditions and pollution levels. Research by [24] showed that DNA analysis of soil surrounding ferns could reveal microbial diversity affected by heavy metal pollution. This technique allows researchers to monitor changes in microbial communities that may be caused by exposure to pollutants [29]. In addition, eDNA is also used to monitor biodiversity and ecosystem health. Research by [31] found that DNA analysis of water and soil around fern habitats can reveal changes in communities of aquatic and terrestrial organisms, providing a more holistic picture of the impact of pollution on ecosystems. By combining eDNA data with physiological and biochemical analyses of ferns, researchers can gain more insight into the interactions between pollution and ecosystems [16]. Overall, using experimental methods, stable isotope analyses, and molecular approaches such as eDNA in the study of ferns as bioindicators provide an invaluable tool for monitoring and understanding the impact of pollution on the environment. Combining these various techniques allows researchers to identify pollution sources, quantify their biological impacts, and develop more effective strategies for future environmental conservation and management [23].

IV. Conclusion

Pteridophytes have proven effective as bioindicators in environmental monitoring, showing high sensitivity to air, water and soil pollutants. Case studies demonstrate the successful use of species such as *Pteridium aquilinum, Polystichum setiferum, Adiantum capillus-veneris,* and *Azolla filiculoides* in detecting sulphur dioxide, nitrogen dioxide, and heavy metals. Research methodologies combining physiological and biochemical measurements and molecular analyses such as eDNA provide comprehensive data on pollution impacts. Multidisciplinary approaches and long-term monitoring are recommended to improve the effectiveness of sustainable environmental monitoring strategies.

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