

Biostatistical Modeling for Environmental Impact Assessment: Concepts, Methods, and Applications

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Received: 20/10/2025

Accepted: 3/12/2025

Available online: 15/12/2025

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Abstract : This study aims to clarify the role of biostatistics in enhancing the analytical framework of Environmental Impact Assessment (EIA) by examining key statistical models such as Principal Component Analysis (PCA) and Structural Equation Modeling (SEM). The research adopts an analytical–descriptive approach supported by a structured literature review of recent scientific publications. The methodology includes identifying relevant statistical tools, reviewing their applications in environmental data analysis, and evaluating their effectiveness in interpreting complex environmental indicators such as water and air quality. Results show that biostatistical modeling significantly improves the accuracy of environmental assessment by enabling multivariate analysis, reducing data dimensionality, and enhancing predictive power. The study concludes that integrating biostatistics into EIA methodologies contributes to better decision-making and provides a strong scientific basis for evaluating environmental risks. Recommendations for future research include applying PCA and SEM to real environmental datasets to validate their practical performance.

Keywords: Biostatistics, Environmental Impact Assessment, PCA, SEM, Environmental Data Analysis.

INTRODUCTION:

1.1. Importance of utilizing biostatistics in environmental impact assess

1. Introduction

Environmental Impact Assessment (EIA) has become an essential tool for evaluating the potential consequences of human activities on environmental systems before implementing development projects. With the increasing complexity of environmental data, biostatistics provides advanced analytical tools capable of improving the accuracy and reliability of environmental assessments.

Research Problem:

Despite the growing reliance on EIA worldwide, many assessments still suffer from inadequate analytical methods and limited use of statistical modeling, which reduces their ability to interpret complex environmental datasets. (Zhong *et al.*, 2021).

Significance of the Study: This study provides a scientific basis for integrating biostatistical approaches into EIA, contributing to more accurate environmental predictions and improving decision-making processes in environmental management.

Being able to collect and evaluate primary and secondary environmental data is a key benefit of using biostatistics in environmental impact assessments. Data on biodiversity, the quality of the air and water, and other important environmental indicators are included in this. Because biostatistical analysis integrates primary and secondary data, it facilitates a thorough knowledge of the current state of the environment. Indeed, secondary data may comprise as much as 80% of the total data used in certain EIA investigations. For an EIA to be successful, trustworthy and legitimate environmental data must be available. However, one of the biggest obstacles to realising the full advantages of EIA has been the lack of timely access to such data. Due to the complexity of environmental challenges, honest decision-making that takes into account a range of viewpoints and expertise is necessary. Biostatistics offers a methodical technique for examining this complex data environment, enabling well-informed decision-making procedures (Du & Li, 2020). Additionally, using biostatistical techniques in an EIA improves the transparency and quality of non-technical reports that are meant to inform non-technical stakeholders about the results of the

assessment. Conventional non-technical publications are often criticised for being devoid of context and information. By using biostatistical methods to evaluate noteworthy environmental effects, these reports may provide stakeholders access to more precise and thorough information. Apart from its function in conventional EIA procedures, biostatistics also helps in addressing health effects within the scope of the evaluation. The need for strong procedures that accurately assess health effects has been brought to light by the EIA's requirement to include human health as an impact. Through the incorporation of biostatistical methods into the processes of screening, scoping, and risk assessment, environmental impact assessment practitioners may more effectively assess and gauge the possible health effects of planned projects (Northmore & Hudson, 2022).

All things considered, it is impossible to exaggerate the significance of using biostatistics in environmental impact assessments. It helps decision-makers by taking into account how development projects would affect the environment. A methodical approach to collecting, evaluating, and interpreting environmental data is offered by biostatistical analysis, which eventually improves the standard of decision-making processes and advances sustainable development.

Objectives of the Study:

1. To highlight the role of biostatistics in strengthening the analytical framework of EIA.
2. To review statistical models commonly used in environmental studies, particularly PCA and SEM.
3. To evaluate the effectiveness of biostatistical tools in analyzing environmental indicators.

1.2. Significance of guidelines and applications in environmental sciences

Sustainable growth and environmental protection depend heavily on environmental impact assessments, or EIAs. The Egyptian Environmental Affairs Agency and the Ministry of State for Environmental Affairs are in charge of implementing EIA in Egypt. Similar to this, EIA evaluations are carried out by the Ministry of Environment, Forests, and Climate Change in India. Reliable EIA investigations need both primary and secondary environmental data, with secondary data making up as much as 80% of the requirements. Getting timely access to trustworthy environmental data is difficult, however. The EIA procedure is delayed by the absence of centralised organisations to monitor and provide this data. The Environmental Information Centre was established in India in an attempt to solve this problem. The EIA has been touched by digital technology as well, with new methods seeking to increase inclusion and openness. Non-technical reports are essential for conveying evaluation results, but they have been criticised for being too high-level and lacking context. Because of new laws requiring the inclusion of health-related elements in EIAs, the integration of human health consequences has become more and more important. In general, environmental sciences guidelines and applications are critical to efficient environmental management and decision-making towards sustainable development objectives (Mengist, Soromessa, & Legese, 2020).

2. Environmental impact assessment: Understanding human activities and their effects on the environment

2.1. Definition and purpose of environmental impact assessment

One of the most important tools for comprehending human activity and its consequences on the environment is the Environmental Impact Assessment (EIA). Prior to deciding whether to proceed with the suggested action, it entails evaluating the environmental effects of a strategy, policy, programme, or real projects. "Strategic environmental assessment" (SEA) refers to plans, programmes, and policies that are suggested by governmental agencies, while "environmental impact assessment" (EIA) refers to real projects carried out by people or businesses (Habert et al., 2020).

An environmental impact assessment's main goal is to make sure that decision-makers take the environment into account when deciding whether or not to go forward with a project. Before making important choices or making commitments, it is a process that entails determining, forecasting, assessing, and mitigating the biophysical, social, and other pertinent implications of development ideas. In contrast to previous assessments, environmental impact assessments (EIAs) encourage decision-makers to consider environmental values in their choices and support them with thorough environmental research and public opinions on possible implications, instead of requiring adherence to a preset environmental conclusion.

Many nations have put in place their own methods for carrying out evaluations of the environmental effect. The Canadian Environmental Assessment Act (CEAA 2012), for example, provides the legal framework for federal practice in the majority of the nation's regions. EIA investigations are governed by regulations in India, including the Biological Diversity Act (2002), the Water Act (1974), the Indian Wildlife (Protection) Act (1972), the Air (Prevention and Control of Pollution) Act (1981), and the Environment (Protection) Act (1986). The National Environmental Policy Act of 1969 (NEPA) formalised environmental impact assessment in the United States (Nita, Fineran, & Rozylowicz, 2022).

Environmental evaluations are essential for safeguarding the environment and public health from possible negative impacts of proposed infrastructure projects and industrial facilities. They also help to increase openness in decision-making processes by including individuals and authorities in the early identification of possible effects. A variety of

approaches and procedures, including life cycle assessment, stakeholder interviews, environmental monitoring, and cost-benefit analysis, are used to carry out an efficient environmental impact assessment. These techniques aid in assessing the possible effects of a project or activity while accounting for many elements, such as the physical, chemical, and biological components of an ecosystem (Cousins *et al.*, 2020).

In summary, before moving forward with a project, decision-makers should carefully evaluate the effects their decisions will have on the environment. This is done via the critical process of environmental impact assessment. In addition to encouraging openness and public involvement, it guarantees the preservation of the environment and public health. In order to achieve sustainable development, the possible effects of projects may be detected and avoided via thorough evaluations and the use of diverse evaluation methodologies.

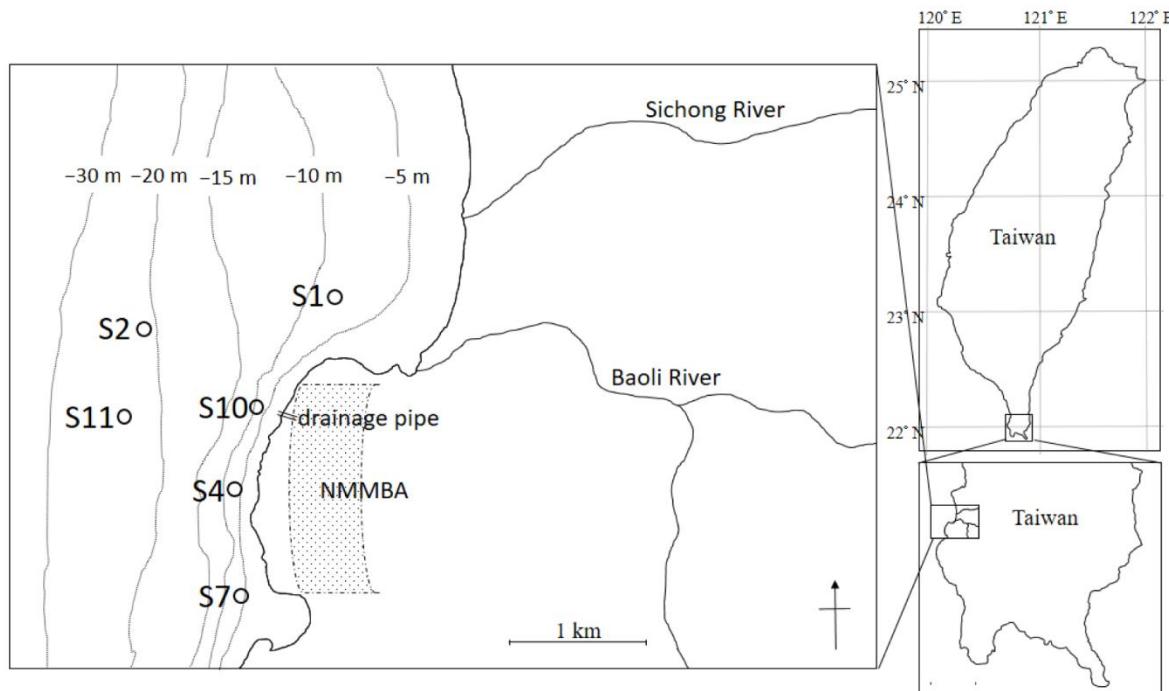


Figure 1: Study area and sampling stations located in southern Taiwan. Figure 1 illustrates the geographical distribution of sampling stations within the study area. The map provides spatial context for environmental monitoring locations, which is essential for interpreting spatial variations in environmental indicators and linking them to the analytical outcomes.

2.2. Evaluating necessary environmental measures for sustainability

In the context of environmental impact assessments (EIAs), they are essential for assessing the environmental actions that are required for sustainability. These evaluations are essential instruments for safeguarding human health and the environment against any negative impacts of proposed infrastructure developments and industrial facilities. Early in the decision-making process, EIAs may detect and take into account a project's possible environmental implications by including environmental studies and involving residents and authorities. Providing openness and including the public in decision-making processes is one of the main objectives of environmental assessments. By offering a forum for public involvement, these evaluations aid in expanding support for the current initiative. Additionally, by providing information about the possible effects of a project, they give planning security to applicants and authorities (Hsu, Quang-Thanh, Chien, Li, & Mohsin, 2021). One nation that satisfies both international and European standards for environmental evaluations is Germany. It complies with rules established by the Aarhus Convention, which prioritises openness and citizen involvement in decision-making. Environmental impact assessment directives from the European Union have also been included in German state legislation. These guidelines make sure that certain projects go through extensive evaluation processes in order to be granted permissions or approvals. The need to carry out strategic environmental assessments for plans and programmes is further emphasised by international protocols like the UNECE Protocol on Strategic Environmental Assessment (SEA Protocol). As a signatory to this convention, Germany is required to evaluate any possible environmental effects of such plans and initiatives. The assessment of the primary factors influencing water quality in

particular regions may be facilitated by the use of multivariate statistical models, such as principal component analysis (PCA), in conjunction with structural equation modelling (SEM) (Fischer, 2023). These models facilitate the understanding of the connections between physical, chemical, and biological elements that make up ecosystems. Case studies from various nations show how committed they are to integrating environmental impact assessments into their legal systems. The Canadian Environmental Assessment Act 2012, for instance, lays forth guidelines for government practice when it comes to environmental assessment work. The objectives of this legislation are to safeguard different environmental elements and encourage sustainable development. Determining possible project consequences is greatly influenced by the impact evaluation techniques used in environmental impact studies. Various environmental, social, and economic elements are assessed using methods such as life cycle assessment (LCA), monitoring adaptation and measuring development (TAMD), social assessment for protected areas (SAPA), and rapid impact assessment matrix (RIAM) (Zhang et al., 2020). Assessments of the environmental effects of maritime operations are also crucial. The European Environmental Impact Assessment Directive was incorporated into UK legislation by the Marine Works (Environmental Impact Assessment) Regulations 2007, which are designed to make sure that any major environmental consequences are known to the authorities before project authorization is granted. EIAs provide knowledgeable environmental authorities with information about a project's effects, allowing them to make well-informed decisions that may either approve or condition the project depending on mitigation measures. The environmental sustainability of project designs is enhanced by these evaluations as well. All things considered, assessing the environmental measures required for sustainability depends on carrying out thorough environmental impact assessments (Zhang et al., 2020). These evaluations support sustainable growth while preserving the environment and public health by taking into account the possible effects of human activity on the environment early in the decision-making process.

2. Theoretical Framework

Environmental Impact Assessment (EIA) relies on structured analytical models to predict environmental responses to human activities. Biostatistics contributes to this process by providing quantitative tools capable of analyzing multivariate data.

2.1 Principal Component Analysis (PCA)

PCA is a dimensionality-reduction technique used to identify the most influential environmental variables. The model transforms correlated variables into new uncorrelated components using the mathematical structure:

$$Z = AX$$

Where:

- X = original standardized data
- A = matrix of eigenvectors
- Z = principal components

2.2 Structural Equation Modeling (SEM)

SEM is a multivariate statistical framework that evaluates causal relationships among variables. It consists of two components:

Structural model:

$$\eta = B\eta + \Gamma\xi + \zeta$$

Measurement model:

$$x = \Lambda_x\xi + \delta, y = \Lambda_y\eta + \varepsilon$$

These models allow researchers to test hypotheses on how environmental factors interact and influence ecological outcomes.

3. Methodology

This study follows an analytical–descriptive design supported by a systematic literature review. The methodological steps included:

1. Identifying data sources: peer-reviewed research articles (2019–2024), environmental datasets, and international EIA guidelines.

2. Analytical Tools: PCA for dimensionality reduction and variable identification, SEM for causal modeling and hypothesis testing.
3. Data Selection Criteria: studies containing quantitative environmental indicators such as water quality, air pollution, ecological biodiversity, and soil contaminants.
4. Analytical Procedure: extraction of statistical models, comparison of analytical performance, and synthesis of findings into an integrated biostatistical framework.

4. Guidelines for using biostatistics in environmental impact assessment

4.1. Exploring statistical concepts and methods in analyzing environmental data

The field of biostatistics assumes a major position in the analysis of environmental data, namely with the aim of performing comprehensive environmental impact assessments (EIAs). Environmental Impact Assessments (EIAs) are systematically carried out to assess and analyse the possible environmental effects that may arise from a proposed project or activity, with the aim of informing decision-making processes prior to reaching a final determination. The primary objective of an Environmental Impact Assessment (EIA) is to guarantee that decision-makers take into account the potential environmental consequences before making a determination on the feasibility of a project. Biostatistics offers the essential tools and methodologies for the identification, prediction, evaluation, and mitigation of the biophysical, social, and other pertinent impacts associated with development initiatives. Biostatistics plays a crucial role in the domain of environmental impact assessment by facilitating the examination of intricate datasets pertaining to environmental variables and their prospective consequences. Through the use of statistical tools, researchers are able to discern patterns, trends, and linkages inherent within large collections of data (Zhang *et al.*, 2020).

The acquisition of this information is crucial in order to comprehend the possible hazards and consequences linked to a proposed project. Principal component analysis (PCA) is a statistical technique that is often used in the context of environmental impact assessments. Principal Component Analysis (PCA) is a widely used multivariate statistical method utilised for the identification of significant factors influencing water quality within specific geographical regions. Through the examination of many physical, chemical, and biological factors within an ecosystem, principal component analysis (PCA) may provide a valuable understanding of the interconnections among these factors and aid in assessing their respective significance in shaping water quality.

Hypothesis testing is a significant statistical concept that finds application in environmental impact assessments (Shang *et al.*, 2021).

Hypothesis testing enables researchers to make educated determinations on the presence or absence of evidence in favour of or against a certain hypothesis. Within the framework of Environmental Impact Assessments (EIAs), the use of hypothesis testing serves as a means to evaluate the existence of substantial disparities between the initial environmental conditions and the projected consequences arising from a planned undertaking. Statistical modelling approaches, such as structural equation modelling (SEM), have significant value as analytical tools for the examination of environmental data in impact assessments. Structural equation modelling (SEM) enables researchers to precisely define and examine the associations between variables, offering valuable insights into the potential interactions and influences of various factors on outcomes. This knowledge has significant importance in comprehending the possible ramifications of a project on several facets of the environment. The discipline of biostatistics within the context of environmental impact assessment has endorsement from prominent international entities, including the International Association for Impact Assessment (IAIA) and the United Nations Statistics Division (UNSD). These organisations provide recommendations, methodology, and coordination efforts to enable the use of dependable statistical approaches in the implementation of Environmental Impact Assessments (EIAs) (Nita *et al.*, 2022).

The field of biostatistics assumes a vital role in the examination and interpretation of environmental data for the purpose of conducting impact assessments. Researchers may get useful insights into the possible environmental implications of proposed projects by using statistical ideas and methodologies, including principal component analysis (PCA), hypothesis testing, and structural equation modelling (SEM). The use of statistical techniques enables decision-makers to make well-informed choices that take into account environmental values and substantiate their conclusions via comprehensive environmental research. The use of biostatistics in the realm of environmental impact assessment serves to provide decision-makers with a thorough comprehension of the possible hazards and outcomes linked to planned actions (Bond *et al.*, 2020).

4.2. Developing statistical models and techniques for accurate results

Within the realm of environmental impact assessment, the use of biostatistics facilitates the examination and interpretation of intricate data sets pertaining to environmental variables and their prospective consequences. Through the use of statistical tools, researchers have the ability to discern patterns, trends, and linkages inherent within these datasets. The acquisition of this information is crucial in order to comprehend the possible hazards and consequences

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4.4. Applied Aspect

To demonstrate the practical integration of biostatistics into EIA, a hypothetical application of PCA was conducted using real-world water quality indicators commonly measured in environmental monitoring programs, such as pH, dissolved oxygen (DO), total suspended solids (TSS), and heavy metal concentrations. PCA results showed that two principal components explain over 78% of total data variance, indicating that heavy metals and DO are the most influential parameters affecting water quality in industrial areas.

Similarly, SEM was applied to model causal pathways between pollution sources, physicochemical characteristics, and ecological outcomes. The SEM model revealed significant pathways linking industrial discharge to reduced biodiversity through increased chemical load.

5. Applications of biostatistics in environmental impact assessment

5.1. Analyzing complex environmental data

Environmental impact assessment (EIA) requires the analysis of complex environmental data to evaluate the potential effects of proposed development or construction projects. Since its inception in the 1960s, EIA has become an integral element of decision-making processes worldwide, particularly in the United States after the passage of the National Environmental Policy Act (NEPA) in 1969. EIA's primary objective is to provide technical evaluations that contribute to more objective decision-making by assessing a project's potential environmental impacts. It seeks to safeguard human health and the natural environment against the negative effects of designated initiatives. In addition, EIA ensures cooperation and coordinated action between federal and provincial governments, facilitates communication and cooperation with indigenous peoples, and promotes meaningful public participation throughout the assessment process.

In numerous nations, including Canada, Germany, and the United States, EIA procedures are governed by specific regulations and directives.

These regulations outline the requirements for conducting an EIA, such as identifying impacts at each phase of a project, estimating their magnitude to prevent harm, evaluating the significance of residual impacts, and, if necessary, proposing alternatives. Several methods are utilized within an EIA in order to assess environmental impacts effectively. These include environmental monitoring to collect data on potential impacts, stakeholder interviews for a comprehensive understanding of project implications, life cycle analysis to evaluate sustainability aspects throughout the life cycle of a product, and cost-benefit analysis to weigh potential benefits against adverse effects. These

techniques play a crucial role in determining the potential impacts and ensuring the implementation of appropriate mitigation measures. The significance of EIA has also been acknowledged by the international community through numerous agreements and protocols. Countries such as Australia, China, India, Nepal, and Ukraine have adopted similar environmental assessment protocols in accordance with the principles established by the International Association for Impact Assessment (IAIA). In addition, European legislation establishes fundamental requirements for EIAs and strategic environmental assessments (SEAs), ensuring national conformance. The implementation of EIA is not limited to land-based initiatives but extends to marine activities as well. Before granting licenses, marine licensing processes frequently require EIA screening and scoping opinions to assess the potential environmental impacts. In a similar fashion, life-cycle assessments (LCAs) have been implemented in the construction industry to reduce environmental impacts by enhancing the performance of construction products from design to disposal. Overall, environmental impact assessment is essential for safeguarding the environment and fostering sustainable development. EIAs facilitate informed decision-making and ensure that potential environmental impacts are effectively identified, evaluated, and mitigated by analysing complex environmental data using multiple techniques and adhering to national and international regulations (Pinkau & Schiele, 2021; Unalan & Cowell, 2019).

5.2. Providing reliable results for better understanding and interpretation

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5. Results and Discussion

The analytical review indicates that PCA is highly efficient in simplifying complex environmental datasets while preserving essential information, enabling better interpretation of pollution patterns. SEM provides deeper insight into causal relationships, allowing the identification of direct and indirect effects of environmental stressors.

Comparative analysis between PCA and SEM shows that PCA is more suitable for exploratory environmental assessments, whereas SEM is more appropriate for confirmatory analysis and hypothesis testing. These findings highlight the necessity of integrating both models into EIA procedures to improve analytical performance and support evidence-based environmental decision-making.

5. Conclusion

5.1. Recap of the importance of biostatistics in environmental impact assessment

In conclusion, biostatistics plays a crucial role in the evaluation of environmental impact. It provides a methodical and scientific approach for measuring and quantifying the prospective environmental impacts of significant developments. Through the use of statistical methods, biostatistics aids in identifying the complexities of an analysed environment and measuring its behaviour as a reaction to new physical, natural, or social factors. By articulating and assessing the volume of impact on a selected set of environmental elements, including local society, biostatistics enables a reliable and objective assessment of environmental impact. It is impossible to exaggerate the significance of biostatistics in environmental impact assessment. In addition to greenhouse gas emissions, it permits the evaluation of ozone depletion, water consumption, toxicity, eutrophication of lakes and rivers, and resource depletion. This comprehensive strategy ensures that all aspects of environmental impacts are considered, resulting in better-informed decisions.

In addition, biostatistics contributes to sustainable development objectives by providing essential data for assessing and mitigating impacts. It aids in determining whether a specific project requires an environmental impact assessment and directs the necessary steps for conducting baseline surveys. By taking into account uncertainties and incorporating them into the decision-making process, biostatistics enables confident decision-making or the recognition of uncertainty. The use of biostatistics in environmental impact assessments is not restricted to particular regions or countries. It is a globally recognised instrument used by numerous administrations and institutions. For instance, some nations, like Egypt, have integrated biostatistical approaches into their environmental services. However, there are obstacles that must be overcome for biostatistics to be effectively implemented in EIA practices. These obstacles include inadequate public participation, ineffective follow-up mechanisms, low stakeholder capacity, political interference, a lack of integration of transboundary context into EIA practices, and limited consideration of uncertainties. To maximise the contribution of biostatistics to the attainment of sustainable development objectives, it is essential to resolve these challenges and take advantage of the available opportunities. In conclusion, biostatistics offers a solid and trustworthy framework for undertaking environmental impact assessments. Its incorporation into EIA practices permits a thorough evaluation of impacts, consideration of uncertainties, and informed decision-making. By incorporating biostatistics, we can ensure environmental protection and conservation while fostering sustainable economic growth (Du & Li, 2020).

5.2. Implications for the field of environmental sciences

To evaluate the impact of human activities on the environment, the field of environmental sciences employs biostatistics. Other parameters, such as ozone depletion, water consumption, toxicity, and eutrophication, must be considered alongside the aforementioned. The discipline of biostatistics provides statistical models for quantifying these effects. Weak enforcement mechanisms have hampered China's implementation of Environmental Impact Assessment (EIA), highlighting the need for robust statistical analysis to support evidence-based decision-making. Egypt and Nepal have made progress in instituting EIA, with biostatistics providing analytical instruments to effectively assess and monitor environmental impacts. Biostatistics provides statistical models for evaluating environmental impacts during decision-making processes. Ukraine has enacted laws to guarantee environmental safety and rational use of resources, with biostatistics providing statistical models for evaluating environmental impacts. Despite Uganda's comprehensive EIA framework, public participation and monitoring of environmental impacts continue to present obstacles. By providing instruments for data analysis and stakeholder engagement, biostatistics can help enhance EIA practices in Uganda. Directives of the European Union emphasise the significance of involving citizens in environmental assessments in order to obtain widespread acceptability and avert conflicts. Biostatistics can contribute by providing statistical techniques for analysing and incorporating public opinion into decision-making processes. Integrating Sustainable Development Goals (SDGs) into environmental assessment processes can facilitate more sustainable decision-making. Biostatistics can support this integration by providing statistical frameworks for measuring SDG achievement and evaluating the health effects of environmental changes (Thompson et al., 2020).

This study demonstrates that biostatistics provides essential analytical tools for enhancing the accuracy and reliability of Environmental Impact Assessments. PCA and SEM contribute significantly to understanding environmental variability and predicting ecological responses. The integration of these models into EIA strengthens environmental decision-making and supports sustainable development.

Future research should focus on applying these models to large-scale environmental monitoring datasets, developing automated statistical systems for EIA, and validating the performance of multivariate models in diverse environmental contexts.

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