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Article

Assessment of aquatic ecosystem quality in Dharoi Reservoir using Sentinel-2 satellite imagery

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Abstract: Background: Dharoi Reservoir, located in Gujarat, India, is a vital freshwater resource supporting agriculture, industry, and local communities. Chl-a, a key indicator of water quality, reflects the trophic state and ecological balance of aquatic systems. **Objective(s):** This study aims to provide comprehensive insights into the water quality dynamics of Dharoi Reservoir, offering valuable information for environmental management and sustainable water resource planning. **Methods:** This study employs high-resolution Sentinel-2 satellite imagery to analyze Chl-a concentrations in the reservoir during October 2020. The Chl-a index, calculated by dividing Sentinel-2 bands B5 and B4, reveals a spatial distribution of Chl-a concentrations. **Results:** The Chl-a index ranges from 73.78 to 100. The mean Chl-a index is 91.6 with a standard deviation of 3.27, indicating elevated and variable Chl-a concentrations. **Conclusions:** The findings contribute to the understanding of the reservoir's ecological health and assist in making informed decisions for water quality management. This research exemplifies the integration of remote sensing technology and environmental stewardship, promoting sustainable water management practices in the region. **Policy recommendations:** One possible policy recommendation is to monitor and regulate the sources of nutrient inputs into the reservoir, such as agricultural runoff, sewage, and industrial effluents, to reduce the risk of eutrophication and algal blooms. Another possible policy recommendation is to implement adaptive management strategies that consider the seasonal and spatial variability of Chl-a concentrations and their impacts on water quality and availability.

Keywords: Dharoi Reservoir; Chlorophyll-a (Chl-a); Sentinel-2 satellite imagery; water quality; ecological health; sustainable water management

1. Introduction

The Dharoi Reservoir, nestled in the vibrant state of Gujarat, India, serves as a lifeline for the surrounding communities [1]. It plays a pivotal role in various sectors, including agriculture, industry, and domestic water supply [2]. However, the reservoir's water quality is not constant and experiences variations due to a combination of natural processes and human activities [3].

Natural factors such as seasonal changes, weather patterns, and biological activities can influence the reservoir's water quality [4]. For instance, during the monsoon season, the reservoir may receive a large influx of water, carrying with it sediments and nutrients that can alter the water's physical and chemical properties. Similarly, biological activities such as algal blooms can affect the water's oxygen levels and pH, impacting its overall quality [5].

On the other hand, anthropogenic factors such as industrial effluents, agricultural runoff, and domestic sewage can introduce pollutants into the reservoir [4,5]. These pollutants can include heavy metals, pesticides, and nutrients, which can pose risks to the reservoir's ecological health and the well-being of the communities that rely on it [6].

Given these challenges, regular monitoring and assessment of the water quality in Dharoi Reservoir are crucial. Such efforts can help identify potential issues early, allowing for timely interventions to mitigate any adverse impacts. Moreover, they can provide valuable data to inform decision-making processes, contributing to the sustainable management of this vital resource [7].

Furthermore, these assessments can guide the development and implementation of effective water management strategies. These strategies can include pollution control measures, watershed management practices, and community awareness programs. By ensuring the reservoir's water quality, we can safeguard its ecological health and continue to support the societal well-being of the communities that depend on it.

One of the key indicators of water quality is Chlorophyll-a (Chl-a), a pigment found in algae and plants that reflects the trophic state and nutrient status of aquatic economic, political, and cultural phenomena from a global standpoint [8–12]. High concentrations of Chl-a may indicate eutrophication, a process of excessive algal growth that can impair water quality and cause ecological imbalance [13,14].

In recent years, there have been advancements in predicting chlorophyll-a concentrations using various remote sensing and ground observation data (**Table 1**). These methods have been shown to improve the spatial resolution and reduce discrepancies between predicted and observed values.

Table 1. The recent studies related to Chl-a concentration estimation using remote sensing and GIS.

Study	Description	Reference
Remote Sensing Estimation of Chlorophyll-a Concentration in Taihu Lake	This study used remote sensing to estimate Chl-a concentrations in Taihu Lake, China. The study considered the spatial and temporal variations of the lake's optical properties.	[15]
Applying Deep Learning in the Prediction of Chlorophyll-a in the East China Sea	This study applied deep learning to predict Chl-a concentrations in the East China Sea. The study used a long short-term memory (LSTM) neural network for training and prediction.	[16]
Prediction of Chlorophyll-a and Suspended Solids Through Remote Sensing	This study used Sentinel-2 spectral images and laboratory analysis data to train an artificial neural network for predicting the concentration of Chl-a.	[17]
Machine and Deep Learning Regression Models for Predicting Chlorophyll-a	This study used machine and deep learning models applied to hyperspectral satellite imagery for predicting Chl-a.	[18]

For Dharoi Reservoir, the current reservoir level data was reported at 187.59 m on 11 January 2024. This records a decrease from the previous number of 187.84 m for 4 January 2024 [19]. The data reached an all-time high of 189.65 m on 26 October 2023 and a record low of 177.99 m on 1 August 2019 [19].

In this study, we aim to explore and assess the spatial distribution and variability of Chl-a concentrations in Dharoi Reservoir using Sentinel-2 satellite imagery, which offers high spatial and temporal resolution for remote sensing applications. We focus on the month of October 2024, which represents a transitional period between the monsoon and post-monsoon seasons, to capture the seasonal variations in water quality.

Our study contributes to the scientific understanding of water quality dynamics in Dharoi Reservoir and provides valuable insights for environmental conservation and water resource management in the region. By utilizing satellite-based remote sensing technology, we offer a holistic and cost-effective approach to water quality assessment that can complement and enhance the existing ground-based methods. We hope that our findings will help foster resilient and sustainable water management practices that can balance the multiple and competing demands on Dharoi Reservoir.

2. Methodology

2.1. Data collection

The study utilized Sentinel-2 satellite imagery from the Copernicus Open Access Hub, specifically the Sentinel-2 Surface Reflectance product, to assess water quality in Dharoi Reservoir. The imagery was acquired during the month of October 2020 to capture seasonal variations in water quality. Additionally, the study incorporated publicly available geographical datasets from Google Earth Engine (GEE) to enhance the analysis [20].

2.2. Calculation of Chlorophyll-a (Chl-a)

The calculation of Chlorophyll-a concentration (Chl-a) involved the use of Sentinel-2 bands B5 (705.4 nm–740.1 nm) and B4 (640.0 nm–672.5 nm), following the algorithm widely used in remote sensing applications [21]. The Chl-a concentration was computed using the formula.

$$\text{Chl-a} = (B5 \times B4) \times 100\text{Chl-a} = (B4 \times B5) \times 100 \quad (1)$$

This computation aims to leverage the spectral properties of Sentinel-2 bands related to chlorophyll absorption and reflectance in water bodies [22]. The resulting Chl-a values were then normalized to the range of 0 to 100 using the clamp function to enhance the interpretability of the data [23]. Water Classification Method: The classification of water bodies was based on Chl-a values, providing insights into different trophic states. The following classification scheme was applied.

- Class 1: Oligotrophic (Chl-a ≤ 10)
- Class 2: Mesotrophic ($10 <$ Chl-a ≤ 25)
- Class 3: Eutrophic ($25 <$ Chl-a ≤ 50)
- Class 4: Hypertrophic (Chl-a > 50)

Non-water pixels were masked out by setting a threshold at Chl-a > 0. The resulting classified image, referred to as ‘Classes’, provides a spatial representation of different water quality states within Dharoi Reservoir [24]. Considerations and Adjustments: In the original code, a few adjustments were made to enhance the functionality and ensure the relevance of the analysis to the study area. Notably, the study focused on Sentinel-2 data from October 2020, a period chosen to capture seasonal variations in water quality. Additionally, the code was modified to export all relevant parameters, including the Sentinel-2 bands, Chl-a concentrations, and water classes, to Google Drive for further analysis and documentation. The implementation of the methodology in Google Earth Engine provides an efficient and scalable platform for remote sensing analysis, allowing for the processing of large-scale spatial data with minimal computational resources (**Figure 1**).

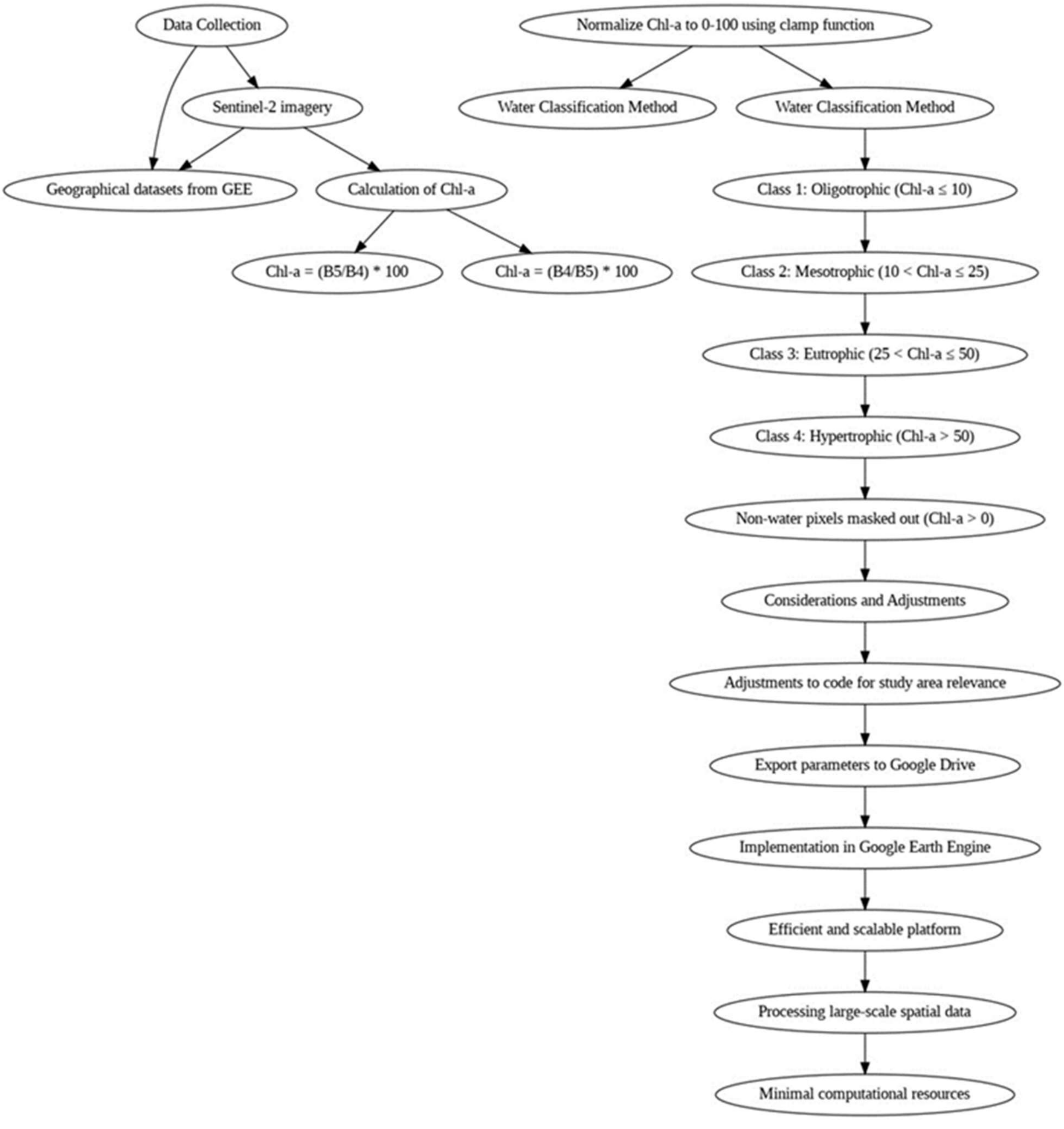

Figure 1. Methodology flow chart of the study.

3. Results

The analysis of Chlorophyll-a (Chl-a) concentrations in Dharoi Reservoir, conducted using Sentinel-2 satellite imagery, revealed a range of values from 73.78 to 100. The Chl-a index, representing the normalized concentration of chlorophyll-a in the water, provides valuable insights into the trophic status of the reservoir.

Chl-a Index Distribution: The Chl-a index varied spatially across the reservoir, with values ranging from 73.78 to 100. The distribution of Chl-concentrations was not uniform, indicating potential hotspots of algal activity or variations in nutrient levels within the water body (**Figure 2**).

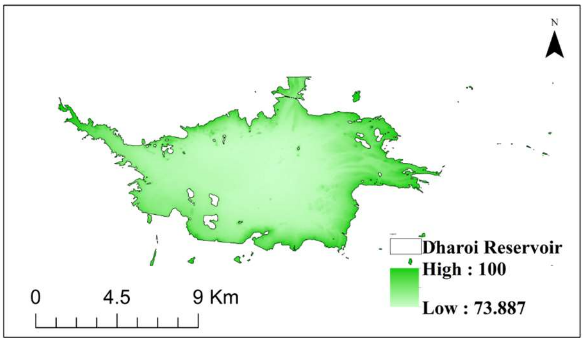

Figure 2. Spatial distribution of Chl-a index in Dharoi Reservoir.

The statistical summary of the Chl-a index in Dharoi Reservoir is presented below:

Mean Chl-a Index: 91.6

Standard Deviation: 3.2

These summary statistics provide a comprehensive overview of the central tendency and variability of Chl-a concentrations in the reservoir. The high mean Chl-a index suggests that, on average, the reservoir exhibits elevated chlorophyll-a levels, potentially indicating a eutrophic condition and hypertrophic condition. The standard deviation provides insights into the variability of Chl-a concentrations, highlighting areas of spatial heterogeneity in water quality.

The observed Chl-a concentrations in Dharoi Reservoir indicate a significant presence of chlorophyll-a, which is often associated with the proliferation of phytoplankton and algae. While elevated Chl-a levels can contribute to the richness of aquatic ecosystems, excessive concentrations may lead to eutrophication, impacting water quality and ecosystem health (**Figure 3**).

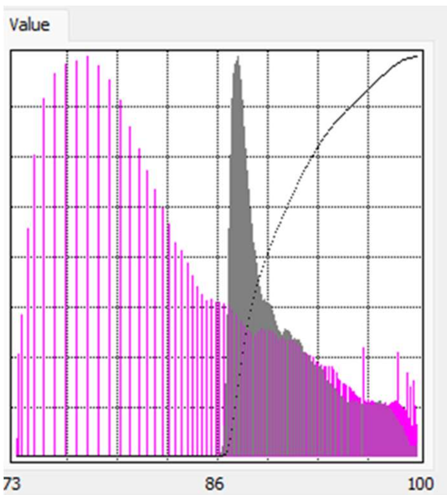

Figure 3. Histogram of Chl-a index.

4. Discussion

These results contribute to a better understanding of the current state of water quality in Dharoi Reservoir, supporting informed decision-making for environmental management and resource conservation [25]. The analysis of Chlorophyll-a (Chl-a) concentrations conducted using Sentinel-2 satellite imagery, provides valuable insights into the trophic status of the reservoir [26]. The Chl-a index, which represents the normalized concentration of chlorophyll-a in the water, varied spatially across the reservoir, indicating potential hotspots of algal activity or variations in nutrient levels [27]. The mean Chl-a index of 91.6 suggests that the reservoir, on average, exhibits elevated chlorophyll-a levels, potentially indicating a eutrophic or even hypertrophic condition. The standard deviation of 3.2 provides insights into the variability of Chl-a concentrations, highlighting areas of spatial heterogeneity in water quality [28].

The histogram of the Chl-a index further illustrates the distribution of chlorophyll-a concentrations in the reservoir. The significant presence of chlorophyll-a, often associated with the proliferation of phytoplankton and algae, suggests that while elevated Chl-a levels can contribute to the richness of aquatic ecosystems, excessive concentrations may lead to eutrophication, impacting water quality and ecosystem health [29].

5. Conclusion

This study has demonstrated the feasibility and utility of using Sentinel-2 satellite imagery to estimate Chl-a concentrations in Dharoi Reservoir, a vital freshwater resource in Gujarat, India. The results revealed high spatial heterogeneity and variability of Chl-a levels across the reservoir, indicating different trophic states and water quality conditions. The mean Chl-a index of 91.6 suggested that the reservoir was generally in a eutrophic state, with high algal biomass and potential risk of harmful algal blooms. The spatial distribution and statistical summary of Chl-a provided valuable insights into the water quality dynamics and ecological status of the reservoir, which are essential for informed decision-making and effective management practices.

This study also highlighted the limitations and challenges of using satellite remote sensing for water quality assessment, such as the influence of atmospheric correction, water depth, and bottom reflectance on the accuracy of Chl-a estimation. Future research should address these issues by incorporating more ground-truth data, improving the calibration and validation of Chl-a algorithms, and applying more advanced methods such as machine learning and neural networks. Moreover, future studies should also consider other water quality parameters, such as turbidity, suspended solids, and nutrients, to obtain a more comprehensive and holistic understanding of the reservoir's ecosystem. Additionally, future studies should explore the temporal variations and trends of Chl-a and water quality in relation to climatic factors, hydrological regimes, and anthropogenic activities.

The findings of this study have important implications for the sustainable management and conservation of Dharoi Reservoir and other similar water bodies in the region. The integration of satellite remote sensing with on-the-ground monitoring and management strategies can enhance the efficiency and effectiveness of water resource management, environmental protection, and public health. This study also contributes to the broader discourse on the role of science and technology in advancing our knowledge and stewardship of complex aquatic ecosystems. As we face the challenges and opportunities of the 21st century, this study underscores the need for continued collaboration and innovation among researchers, policymakers, and stakeholders to safeguard our invaluable water resources.

Author contributions: Conceptualization, SK and SKS; methodology, SKG; software, SKS; validation, SKG, SKS and SK; formal analysis, SKG; investigation, SKG; resources, SKS; data curation, SKG; writing—original draft preparation, SKG; writing—review and editing, SK; visualization, SK; supervision, SKS; project administration, SKS; funding acquisition, SKG. All authors have read and agreed to the published version of the manuscript.

Conflict of interest: The authors declare no conflict of interest.

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Article

Waste water treatment through microalgae and cyanobacteria

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Abstract: Resource recovery systems for microalgae and cyanobacteria could substantially advance the recovery of nutrients from waste water by reaching the rate of effluent nitrogen (N) and phosphorus (P) below the current technology limits. However, the efficient introduction of phytoplankton involves the creation of process models that retain efficiency and simplicity in order to effectively replicate complex performance in response to environmental conditions. This research synthesises the variety of model structures that have gained from the modelling of algae and cyanobacteria and the key model features needed to allow reliable process modelling in water resource recovery facilities. Processes of cyanobacteria, including comprehensive growth prediction guidelines (under phototrophic, heterotrophic and mixotrophic conditions), nutrient absorption, carbon absorption and accumulation, and respiration are provided.

Keywords: microalgae; cyanobacteria; wastewater; biosorption; heavy metal

1. Introduction

Microalgae are microscopic and photoautotrophic cell factories given the rapid nutrients and Carbon dioxide absorption, with a high surface-to-volume ratio, with much accelerated cell proliferation. They have much higher photosynthetic efficiency and they are known to be the main atmospheric carbon synthesizers in marine environments. Micro-algae have been used in food products for human health since ancient times [1].

They feed on fish and poultry, have oils of high importance, additives, pharmaceuticals and pigments. Waste from factories that contaminate the sludge with contaminants, especially heavy metals, which are toxic if present in expanded quantities, are often found in sewage waste [2]. Without adequate treatment, an enlarged amount of sewage effluent is pumped into the marine system, deteriorating its aesthetic appeal. In addition to heavy metals, high concentrations of nutrients (especially N and P), high levels of biodegradable organic matter, fertilisers, pesticides and bad odour are recorded to contain sewage effluent. Not only does untreated waste cause eutrophication, but because of the possible involvement of multiple forms of pathogens, it is also a major health threat [3].

The danger when domestic and industrial waste is combined is so serious. In certain cases, over time, the amount of toxins is amplified, which eventually leads to a change in bacterial and algal communities into more tolerant species such as planktonic cyanobacteria, especially in the warm seasons, dominating the lake water. This species can be distinguished by their greater capacity to withstand such elevated levels of toxins and their productivity in degrading and storing heavy metals from extremely persistent organic contaminants [4]. They could also be used successfully in emerging technology for waste effluent bioremediation. The handling of waste water by microalgae cultures did not produce excess emissions when the biomass is harvested. Around the same time, it encourages proficient nutrient recycling. Several microalgae, like cyanobacteria, have been known to be used in wastewater treatment for many years [5].

Some of the microalgae strains that provide a decent alternative for biological treatment of agro-industrial waste water are *Chlorella vulgaris, Scenedesmus dimorphus, Nostoc muscorum and Anabaena variabilis, Plectonema, Oscillatoria, Phormidium and Spirulina* [6]. In the suspension community, the chosen environmental cyanobacteria species work effectively. Their use is well known for the comparatively limited period of the elimination of organic (BOD, COD, fats, oils and grease) and inorganic (Zn and Cu) as well as physical pollutants (solids, suspended and dissolved) from combined domestic-industrial waste water [7]. In addition to this, cyanobacteria are able to acclimatize quickly and produce many useful compounds in harsh conditions [8].

Few waste contaminants (including heavy metals and salts) will not be transformed into harmless products and may stay indefinitely in the ecosystem, but many other contaminants (including organic chemicals and pathogens) may be reduced at various rates to harmless components [9]. Increased eutrophication of aquatic environments can result from a rise in human population, upcoming factories and townships and the release of untreated sewage in water bodies [10]. The separation of ions by conventional techniques is incredibly costly and an endeavor that absorbs resources. The use of biological processes, however, acts as a cheap and reliable means of extracting nutrients and heavy metals from waste water. In recent years, microalgae have received greater interest, especially as an alternative bio-system for wastewater treatment throughout the tropical and subtropical areas.

Traditionally, algal systems have been used as a tertiary treatment method and they have recently been introduced as a future secondary treatment mechanism. Recovery from the processed effluent is one of the main challenges with the use of microalgae for waste water management. The technology of immobilization, which locks the cells of the microalgae into a matrix, solves the issue of harvesting to a substantial limit. A greater degree of organizational stability and fast separation are enabled by this technology. In immobilized algal biomass, several authors have recorded higher nutrient reduction efficiency than the freely suspended cells of the same genus. The choice of new biological wastewater treatment systems is primarily based on the needs of the human populations and the cost effectiveness of the systems [11].

Multiple strains of microalgae are not similarly successful in the handling of waste water. Their utility in the treatment of waste water depends primarily on two key parameters: (i) the ability of the strains of microalgae to thrive under prevailing environmental conditions and (ii) their pollutant removal performance. The activity and performance of wastewater treatment plants in areas with temperate environmental conditions (very cold/very hot and low insulation/high insulation) relies on the preference of microorganisms that are capable of proliferating under particular harsh environmental conditions. Therefore, strains of microalgae intended for remediation must pass the scrutiny of local drainage system adaptability [12].

1.1. Wastewater treatment by microalgae and cyanobacteria

Ponds used for the treatment of wastewater treatment as well as commonly used for the study of treatment processes can be classified into four major groups: maturation ponds, optional ponds, high-rate algal ponds and seedling ponds of algae [13]. A strategy for combining multiple ponds into a system called 'Advanced Integrated Wastewater Ponding System (AIWPS)' was also advocated for the treatment of microalgae wastewater. However, out of the major forms of algal ponds, high-rate algal pond is considered as one of the well-organized schemes for wastewater treatment. In addition, the function of High-Rate Algal Pond (HRAP) in secondary sewage effluent treatment has been extensively studied. HRAP systems were first considered for wastewater treatment by Oswald and later were used in other parts of the world [14].

1.2. Nutrients removal from wastewater

A huge number of nitrogenous compounds such as nitrate, urea, ammonia, amino acids, and nitrite can be digested by cyanobacteria. Atmospheric nitrogen (N_2) can also be assimilated by diazotrophic cyanobacteria. Since the reduction of dinitrogen gas by nitrogenases to ammonia is a highly exergonic process, in the form of ATP, metabolic energy is needed [15]. The ability to extract nutrients in the absence of organic carbon has commonly been used in algal pond systems for wastewater treatment. On the basis of morphological and molecular studies from the waste stabilization pond system of Sao Paulo, Brazil, the cyanobacterial genera *nostoc, limnothrix, Leptolyngbya, merismopedia* and *synechococcus* were isolated and identified. Several experiments on various scales have been undertaken to affirm the high potential of cyanobacterial organisms to extract nutrients (P and N) from polluted media and structures [16].

2. Removal of heavy metals

Heavy metals have been introduced into the atmosphere over long stretches of time by the actions of humanity. Zinc, nickel, cadmium and copper are probably the most toxic elements commonly present in significant concentrations in waste sludge. Upon release into the atmosphere, it becomes impossible to extract heavy metals by physical and/or chemical processes, and most of them have toxic effects on a broad variety of species. Sewage heavy metals bind to the organic matter that collects in the sedimentation tanks. Although the original concentration of metals might be very small, they are accumulated in the sludge by the removal of water. Precipitation, such as ion exchange, hydroxides/sulphides and oxidation/reduction, are the traditional methods used for waste effluent treatment [17]. These chemical treatments for the recycling of effluent metals before they leave the plant are not environmentally safe and costly. Therefore, the use of microbes, especially microalgae as biosorbent for metal removal, has recently created a considerable amount of interest. Microalgae are the ideal biological tool for waste water disposal because they increase the O_2 content of the water by photosynthesizing and removing some heavy metals from polluted water. Photosynthetic prokaryotes are cyanobacteria; many of them have a significant affinity for heavy metals. Additional methods for extracting heavy metals from waste water, on the other hand, have been invented [18].

2.1. Biosorption of heavy metals

Microalgae biomass biosorption of heavy metals has become an important factor in the integrated approach to aqueous effluent care. Changes in the structure of the cell wall on which the binding of metal ions takes place, as well as variations in their development under various conditions, are due to the selective absorption or degradation abilities of the chosen organisms. Multiple processes such as adsorption, ion exchange, chelation and diffusion through cell walls consist of biosorption. At the cellular level or microbial group level, these passive processes may take place. The active form of metal uptake and concentration, on the other hand, is called difficult bioaccumulation, which relies on the metabolism of cells. On prolonged interaction with the metal bearing solution, the living biomass is also able to sequester intracellular metal by an active mechanism requiring energy expenditure.

Bioaccumulation is treated as a process based on growth and is to be represented in a variety of effluents opposed to growth-independent biosorption. Consequently, in biosorption, microbial biomass can be used and exploited to a degree more effectively than bioaccumulation. The key benefits of biosorption metal recovery include the low cost and high performance of eliminating heavy metals from dissolved solutions. However, techniques would have to be built to quickly eliminate heavy metals from biomass in order not to merely relocate heavy metal contaminants [19]. The bioaccumulation of heavy metals on the surface of algae cells relies on a variety of factors, ranging from inorganic ion concentration, dissolved organic matter, pH, and particulates [20].

2.2. Step by step wastewater treatment process

The process of waste water treatment in step-by-step manner is as follows:

1) Wastewater collection: In the waste water management process, this is the first step. In order to ensure that all waste water is collected and hits a central location, recycling schemes are placed in place by city government, home owners and business owners. Via underground irrigation systems or by exhaust tracks owned or run by business owners, this water then goes to a treatment facility. However, in hygienic terms, the transmission of waste water should be carried out. The pipelines or tracks must be leak proof, or protective equipment must be worn by the persons providing the draining services [21].
2) Odor control: Odor regulation is highly necessary in the treatment plant. Wastewater comprises many polluted compounds that, over time, create a foul smell. Odor treatment procedures are initiated at the treatment facility to ensure that the surrounding environments are free from the foul smell. Using chemicals to neutralize the foul smell produced by components, all odor sources are contained and processed. In wastewater treatment facilities, this is the first and very critical step [22].
3) Screening: This is the next step in the method of wastewater treatment. Screening includes removing large items, such as nappies, cotton buds, plastics, diapers, rags, sanitary goods, nappies, face wipes, broken bottles or bottle tops that can break the equipment in one manner or another. Failure to analyze this step results in persistent issues with machinery and appliances. Specially constructed

equipment is used to collect free sand that is often washed by rainwater into the sewage pipes [23].

4) Primary treatment: The division of macrobiotic solid matter from waste water is involved in this process. For the solid matter to settle on the top of the pipes, primary treatment is carried out by deep waste water in large tanks. The solid waste slush that collects on the surface of the tanks is removed by large scrappers and forced to the middle of the cylindrical tanks for further treatment and then drained out of the tanks. For secondary treatment [15], the remaining water is then pumped.
5) Secondary treatment: The secondary treatment stage, also known as the triggered slush process, includes applying seed slush to the waste water to ensure that it does not fail to function. First, air is injected into massive aeration tanks that combine the waste water with the seed slush, which is actually a small volume of slush, which fuels the production of oxygen-using bacteria and the growth of other small microorganisms that eat the residual organic matter [24]. This method contributes to the creation of huge particles at the bottom of the massive tanks, which settle down. For a time of 3–6 h, the waste water flows into the major reservoirs.
6) Bio-solids handling: The solid matter that remains out is attached to the digesters during the main and secondary treatment processes. At room temperature, the digesters get agitated. The solid waste is then processed for a month where anaerobic digestion is performed. Methane gases are produced during this process and there is a growth of nutrient-rich bio-solids that are used in restricted companies in addition to dewatering. The methane gas emitted is commonly used in treatment plants as a source of energy [25]. This gas can also be used in boilers to generate heat for digesters for the production of electricity in engines or for the production of plant apparatus only.
7) Tertiary treatment: This process is identical to the one used for drinking water treatment plants for drinking purposes that clean raw water. Up to 99 percent of the impurities from the waste water will be eliminated from the tertiary treatment process. It creates effluent water that is similar to the consistency of potable water. Unfortunately, since it requires special equipment, well-trained and highly qualified apparatus technicians, chemicals and a constant supply of energy [26], this method appears to be a little costly.
8) Disinfection: There are also some pathogens that cause species in the residual processed waste water behind the primary treatment stage and the secondary treatment process. In order to extract them, the sewage water must be disinfected in tanks containing a combination of chlorine and sodium hypochlorite for at least 20–25 min. The method of disinfection is an important part of the process of treatment since it preserves the welfare of the animals and the local residents who use the water for other uses [27]. During local water paths, the dust (treated sewage water) is later released into the atmosphere.
9) Slush Treatment: Throughout the main and secondary treatment methods, the slush that is formed and composed involves concentrating and thickening to allow further output. It is deposited in thickening tanks to allow it to settle down and detach from the water later. It can take up to 24 h to perform this method [28].

The leftover water is gathered and sent for further treatment back to the immense aeration tanks. The sludge is then collected and sent out into the atmosphere and can be used for agricultural use. There are a variety of advantages to wastewater treatment [29].

3. Conclusions

For more than five decades, microalgae wastewater treatment has been studied as another environmental noise to eliminate nutrients and heavy metals from wastewater and thereby restore their efficiency. Due to their fast ammonium and nitrate ingestion, phosphate removal of heavy metals, modulation of physico-chemical properties of sewage waste matter and fast growth rate, several cyanobacteria organisms have been unemployed and established as a working model for such studies. Some schemes have been introduced that could contribute to more strict principles of waste matter for water treatment services located in ecologically vulnerable areas. Based on several variables, nutrient reduction efficiency, along with algal organisms, immobilization matrix, concentration of cells and beads, aeration, and preservation time, may be improved. In addition to cation concentrations, metal uptake is also influenced by light strength, pH, biofilm density, the presence of wet metal binding substances, and the resistance of individual algal species to particular heavy metals. Water hardness is a crucial factor affecting the efficacy of metal uptake because cations such as Ca^{2+} and Mg^{2+} compete with trace metals for binding sites Their potential for accelerated genetic alteration is an added advantage that could in future contribute to efficiency changes in cyanobacteria for the remediation of waste water. Microalgae have been described as effective agents to extract natural matter from impure water and, subsequently, to minimize BOD and COD. Using effective strains in fixed applications such as biofilm or immobilized cells, their ability to eliminate multi-contaminants can be seriously improved.

They may also be seen as an association with the actual role in its place, which can greatly shorten the treatment period needed for the greatest elimination. Microalgae have been found to be a more cost-effective way than activated slush to strip away the need for oxidative oxygen, bacteria, phosphorus and nitrogen. The economic potential for the treatment of microalgae wastewater can be further increased by linking the production of microalgae biomass with the treatment of wastewater and thus using resourceful methods for biomass harvesting and exposure to air metabolic and genetic engineering, approaches to systems biology, effective strain selection and high-value co-product strategy. These technologies allow microalgae to be used in polluted systems as an inexpensive and low-protection technology. The beneficial role of microalgae is still not optimally manipulated in the remediation of polluted waters in natural or manmade aquatic ecosystems. The role of bioremediation using original strains of microalgae for the sanitization of impure conjugal and industrial effluents with natural pollutants and heavy metals offers a feasible and safe solution to environmental property monitoring.

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Article

Modeling soil organic carbon based on field soil-texture measurements

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Abstract: There are many studies about soil organic carbon (SOC) around the world but, in extensive territories, it is more difficult to obtain data due to the number of variables involved in the models and their high cost. In large regions with poor infrastructure, low-cost SOC models are needed. With this in mind, our objective was to estimate the SOC using a simple model based on soil textural data. The work was focused on savanna soil and validated the model in the Brazilian Savanna. Two models were constructed, one for topsoil (0–0.3 m) and other for subsoil (0.3–1.0 m). The SOC models can be carried out in a textural triangle together with SOC values. The results showed that subsoil models were more accurate than topsoil models, but both had good performance. The models give support to SOC-related preliminary research in gross and fast estimates, requiring only reduced financial contribution to calculate SOC in a large region of interest.

Keywords: soil organic carbon; soil texture; model; savanna

1. Introduction

Many authors have been estimating the soil organic carbon (SOC) content for years because the data allow interpretation of soil conservation conditions in both natural [1] and anthropic areas [2]. One good advantage is that results help to understand the damage caused by human actions in nature [3].

SOC modelling often employs machine learning techniques [4] based on several soil parameters and properties (textural data, N, pH, Ca^{2+}, Mg^{2+}, Al, Fe), and their covariates related to climate, organisms, topography, parent material, time and site [5,6]. However, the availability of these extensive datasets can often be limited or lacking in certain study sites, particularly in regions with limited financial resources and skilled labor for database construction [7], as commonly observed in tropical savannas of countries like Brazil. As highlighted by Mutuku et al. [8], smallholder farmers usually cannot afford soil laboratory tests, and methods for visual soil evaluations need to be developed.

Garsia et al. [9] evaluated the effectiveness of 221 soil organic carbon models and found that most of them are not validated (71%), only just four included Brazil as a study area. Despite being one of the world's biodiversity hotspots [10], the Brazilian Savanna has experienced significant deforestation, losing over 50% of its native vegetation cover due to agricultural expansion [11]. It is expected that changes in land use-cover affect the SOC in the whole national territory, as we found in several other regions of the world [3,12–15]. However, as in other countries, it is difficult to study SOC in the whole Brazilian territory due to its large extension and the soil data are highly discontinuous in the territory [16].

In this context, it is usual to find studies that rely on a limited number of samples, highlighting the challenge of scarce soil data and without methodological validation. Zinn et al. [17], for example, examined the relationship between soil texture and SOC in Brazilian Savanna soils, analyzing 17 soil samples across seven different depths. Ruggiero et al. [18] investigated the correlation between vegetation and soil properties in the Brazilian Savanna by randomly sampling 10 quadrants of 10 × 10 m. They discovered that soil properties were more closely associated with variations in vegetation physiognomy in the superficial soil layers than at deeper depths. Neufeldt et al. [19] also studied Brazilian Savanna Oxisols, focusing on the effects of texture and land use on soil organic matter (SOM). Their study, based on five undisturbed topsoil samples, concluded that SOM content was correlated with the clay fraction. These studies, while informative, based on a small number of samples, are often related to low financial resources and skilled labor to construct strong systematic datasets [7,20].

We know that it is vital to understand SOC behavior as well as the consequences of agricultural activities. Thus, it is crucial to create ways to allow SOC estimates—with efficiency, effectiveness, and low cost—in large territories and from information easily obtained. Bearing this in mind, we aim to elaborate a model to obtain an exploratory estimate of the SOC based on soil textural data in Brazilian Savannas—the simpler parameter to be evaluated in the soil. This approach should prove valuable for areas where intensive soil surveys and analytical efforts are not feasible.

2. Materials and methods

We developed SOC models based on three steps: dataset organization; mathematical models' construction; and validation under different land use-cover (**Figure 1**).

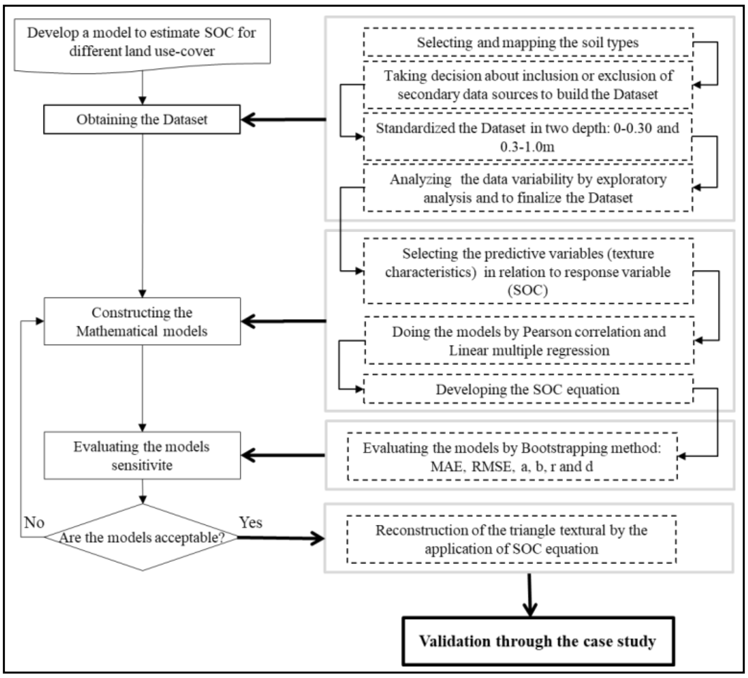

Figure 1. Framework of procedure used.

Data source and analysis methods

The study area was the Brazilian Savanna (Cerrado Biome), covered with natural vegetation or pasture and sugarcane, totaling more than 2 million km^2, equivalent to 22% of the national territory [21]. Due to its large extension, three climate zones are found: (a) the largest one is tropical climate with 88% of the area, (b) 11% of the area is humid subtropical climate, and less than 1% is dry climate [22]. The average annual temperature varies from 20 ℃ to 26 ℃, and the average annual precipitation from 1000 to 1800 mm. Soil fertility is the key factor in determining the Savanna biome vegetation [23]. To represent this diversity, we collected data from the predominant soil type, Oxisols, occupying 41% of the biome [24] in the three climatic zones (**Figure 2**), with natural vegetation and farming production. The remnants of Savanna are established on ancient soils, which are acidic, depleted of nutrients, and rich in aluminum [25,26]. The vegetation upon these soils displays a mosaic of the structures from savanna-like formations to forests.

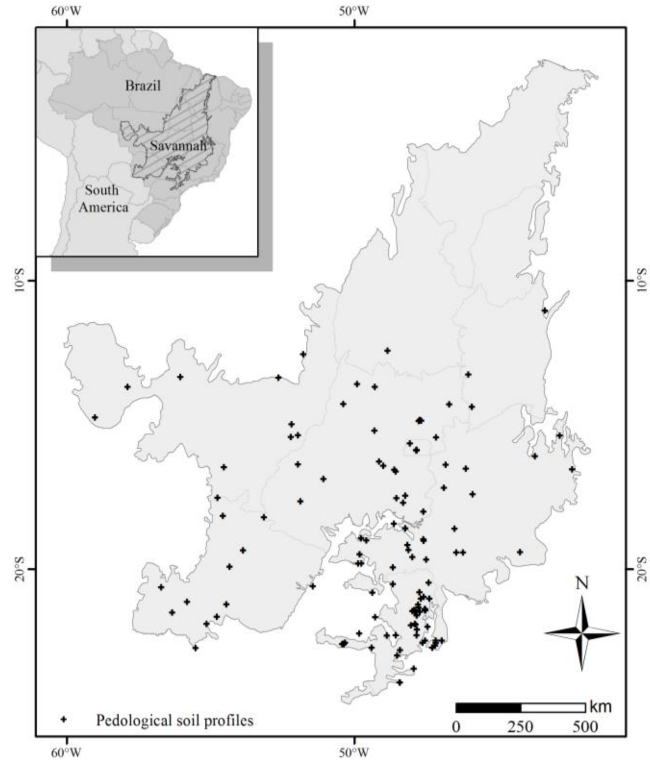

Figure 2. Cerrado soil data distribution obtained from literature review on pedological profiles and ground surveys.

The 10,796 data points were obtained from secondary sources of pedological profiles and ground surveys. They were stored in an information system operated as an Open Access library of the georeferenced data PANGAEA [27]. The dataset considered all pedological profiles to have at least four depths sampled up to a minimum of one meter and located in natural vegetation, pasture, or sugarcane according to Landsat satellite images from soil analysis dates. The available dataset is limited to the savanna center-south region.

The textural data were submitted to a quadratic spline function of the same area

(λ = 0.1) [28,29] using a MATLAB routine [30] to obtain the average values of sand, clay, and silt for two depths, 0–0.3 m (topsoil layer) and 0.3–1.0 m (subsoil layer) as it was done for the SGDBE (Soil Geographical Database of Europe). We checked the dataset variability by mean, standard deviation, and coefficient of variation in Minitab program excluding the outliers. The Pearson correlation method was applied to identify the textural factors (predictable variable) that could be correlated with SOC (response variable), with 0.01 < *p*-value > 0.5. The correlated data in the two depths were included in the linear multiple regression and stepwise (forward and backward) to adjust the SOC estimation models in the statistical program Minitab [17,31,32].

The acceptability of the models was evaluated by mean absolute error (MAE), root mean square error (RMSE), concordance index (*d*) and linear coefficient (*a*), angular coefficient (*b*) and correlation coefficient (*r*) applying the bootstrap method [33] coded in MATLAB [34] for 10.000 iterations. The accepted models were validated by 350 soil points (139 points for 0–0.3 m and 211 points for 0.3–1.0 m) located in the Brazilian Savanna with different depths by MAE, RMSE and Adjusted *R*-squared (R^2).

To explore the potential of elaborating SOC maps from the models proposed in this work, we elaborated a SOC map for São Paulo State—Brazil. We obtained the soil textures from the Pedological Map of São Paulo State [35] and estimated the SOC values from a textural triangle. For this area we have 14 SOC values for topsoil and 40 for subsoil obtained in field points and with lab analysis. Then, we calculated the percentual concordance between these values and the estimated values by the triangle to the same points as a way of evaluating the effectiveness.

3. Results

3.1. Application of the mathematical models in study case

The 10,796 Oxisols soil data points were submitted to a quadratic Spline function obtaining 164 pedological profiles for 0–0.3 m depth and 164 profiles for 0.3–1.0 m, composed of 656 data points of sand, clay, silt, and SOC. These soils displayed textural data values with large-scale variability, from 92 to 515 g·kg^{-1}, and high standard deviations (**Table 1**). The dataset covers all the textural variation characteristics of Oxisols [4]. The layer 0–0.3 m had higher SOC values (1.2 g·kg^{-1} < SOC < 47.1 g·kg^{-1}) than the layer 0.3–1.0 m (1.0 g·kg^{-1} < SOC < 14.7 g·kg^{-1}). The SOC data present normality for both layers by the Anderson-Darling Test (Appendix **Figure A1**).

Table 1. Statistical variation for four soil attributes in two depths.

Depth (m)		Sand (g·kg^{-1})	Silt (g·kg^{-1})	Clay (g·kg^{-1})	SOC (g·kg^{-1})
0–0.3	(a)	514.3 ± 268.2	101.7 ± 70.0	383.9 ± 223.3	13.3 ± 7.8
	(b)	52.2	68.8	58.2	58.6
0.3–1.0	(a)	473.2±265.2	92.2 ± 64.2	434.8 ± 230.4	6.7 ± 3.0
	(b)	56.1	69.6	53.0	45.5

(a) Mean standard deviation; (b) coefficient of variation (%).

The clay and sand data were correlated with SOC by Pearson correlation (**Table 2**), presenting a direct positive correlation between clay and carbon, and an inversed negative correlation with sand.

Table 2. Pearson correlation for SOC response variable.

Depth (m)	Response variable	Sand	Silt	Clay + Silt	Clay
0–0.3	SOC	−0.63	0.38	0.63	0.64
0.3–1.0		−0.72	0.35	0.72	0.74

The best models obtained by multiple linear regression were two for each depth (**Table 3**).

Table 3. Predictive models of SOC ($g \cdot kg^{-1}$) occurring at two depths in soils.

Depth (m)	Models	R^2
0–0.3	SOC = 580 − 0.575 × Sand − 0.557 × (Clay + Silt)	0.44
0–0.3	SOC = 4.771 + 0.02235 × Clay	0.41
0.3–1.0	SOC = 2.452 + 0.009743 × Clay	0.54
0.3–1.0	SOC = 3 − 0.00057 × Sand + 0.0091 × Clay	0.54

3.2. Evaluation of the models sensitive

All the models presented a significant regression ((b) ≠ 0) and were more adjusted in the subsoil layer ((a) closer to zero). The statistical parameters ((MAE); (RMSE)) of this study also indicated the topsoil layer with low performance, which the SOC was overestimated in 5 $g \cdot kg^{-1}$. The concordance index (d) agreed with the MAE/RMSE, ranging from 0.33 to 0.45 (**Figure 3**; Appendix **Figure A2**). For the subsoil layer (0.3–1.0 m) the SOC was overestimated in approximately 1.8 $g \cdot kg^{-1}$ and (d) was near to 0.52. The correlation coefficient (r) indicated the subsoil layer (0.3–1.0 m) as a better combination between the real SOC and the estimated SOC than the topsoil layer models.

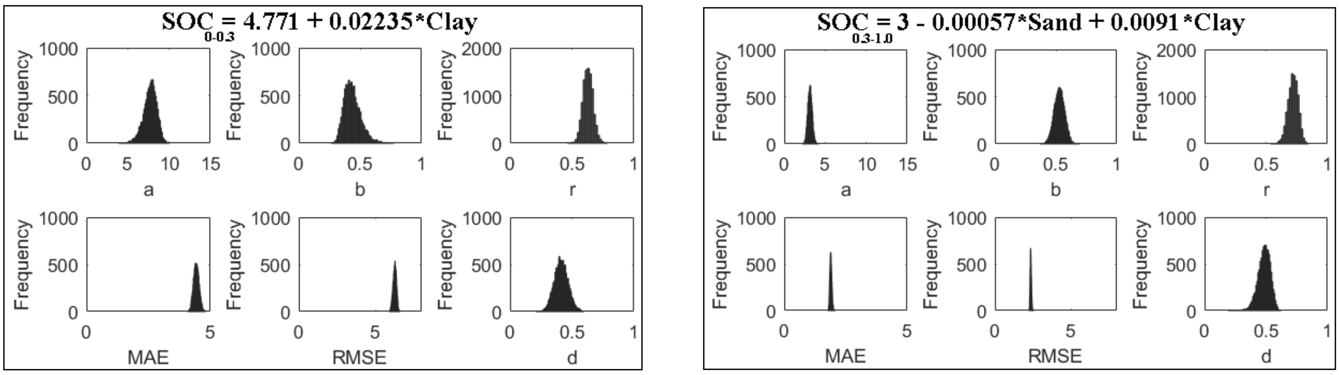

Figure 3. The values estimated by the bootstrap for the best models in the two depths were representing by the histograms above, where (a) linear coefficient, (b) angular coefficient, (r) correlation coefficient, (MAE), (RMSE) and (d) statistical parameters.

These equations resulting from the SOC models provided the basis to estimate SOC based on a textural triangle [36] and making it possible to create a new triangle by placing the estimated values of organic carbon on the points of junction of textural values. The best equations are represented in the **Figure 4** and the others can be seen in the Appendix **Figure A3**.

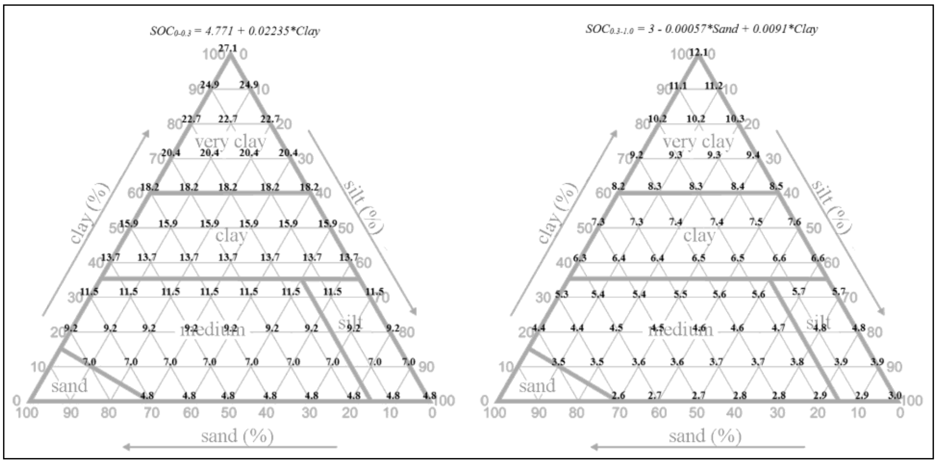

Figure 4. Estimated SOC (g·kg^{-1}) in Savanna Oxisols based in the textural triangle.

3.3. Models validation

The clay values of 139 data points were inserted in the textural triangle which represents the topsoil (**Figure 4**) to estimate the SOC. Then, these values were compared with the measured SOC presented in their respective studies (**Figure 5**). The same approach was utilized for the subsoil (0.3–1.0 m) but with clay and sand data from 211 data points.

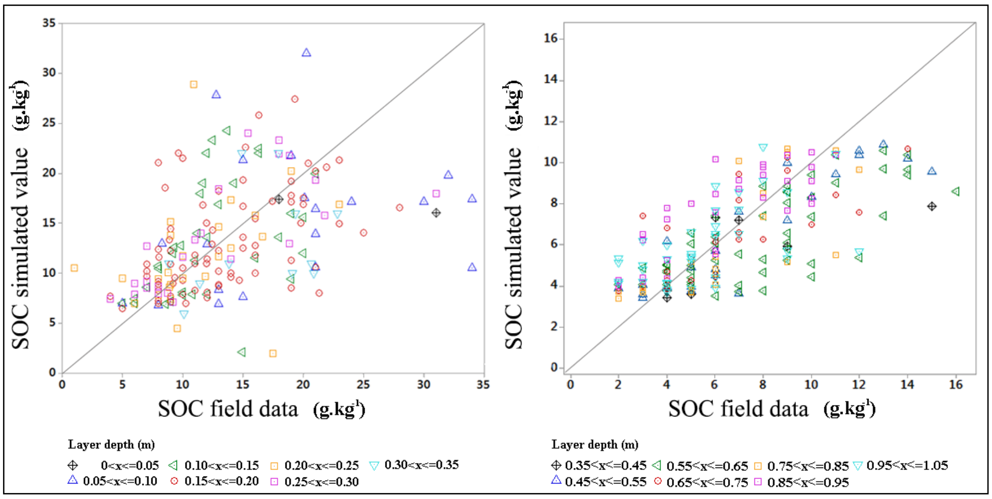

Figure 5. Field measuring versus simulated value of the soil SOC by the textural triangle.

The statistical parameters ((MAE); (RMSE); (R^2)) of the study case indicated the topsoil layer with lower performance than the subsoil (**Table 4**).

Table 4. Statistical tests applied to check the agreement between simulated and observed values, where n is the number of data used in each depth.

Statistical parameters	Depth (m)						
	0 < x ≤ 0.05	**0.05 < x ≤ 0.1**	**0.1 < x ≤ 0.15**	**0.15 < x ≤ 0.2**	**0.2 < x ≤ 0.25**	**0.25 < x ≤ 0.3**	**0.3 < x ≤ 0.35**
RMSE	10.6	9.7	3.9	4.7	3.7	5.4	6.5
MAE	8	7.8	3.1	3.5	2.6	4	5.6
R^2	-	0.2	0.5	0.3	0.5	0.5	0.1
n	2	16	18	57	18	17	11
	0.35 < x ≤ 0.45	**0.45 < x ≤ 0.55**	**0.55 < x ≤ 0.65**	**0.65 < x ≤ 0.75**	**0.75 < x ≤ 0.85**	**0.85 < x ≤ 0.95**	**0.95 < x ≤ 1.05**
RMSE	3	2	2.7	1.9	1.9	2	2.1
MAE	2	1.6	2.1	1.5	1.5	1.7	1.6
R^2	0.4	0.8	0.5	0.6	0.6	0.7	0.3
n	7	24	56	28	23	33	40

We also applied the estimated SOC values in Pedological Map of São Paulo State [35], with the aim to assert the effectiveness of the models. We investigated part of the Brazilian Savanna (Sao Paulo State Savanna), which in turn had less environmental variability in terms of climate, relief, and land use-cover, then with expectations of good results for topsoil [13]. The soil organic carbon mapping represented in **Figure 6** is an expression of the indirect measure obtained by the textural triangle. Our results presented an accuracy of 86% for topsoil and 70% for subsoil. However, if the analyzes were made between 0.6 m and 1 m, the accuracy goes up to 80%.

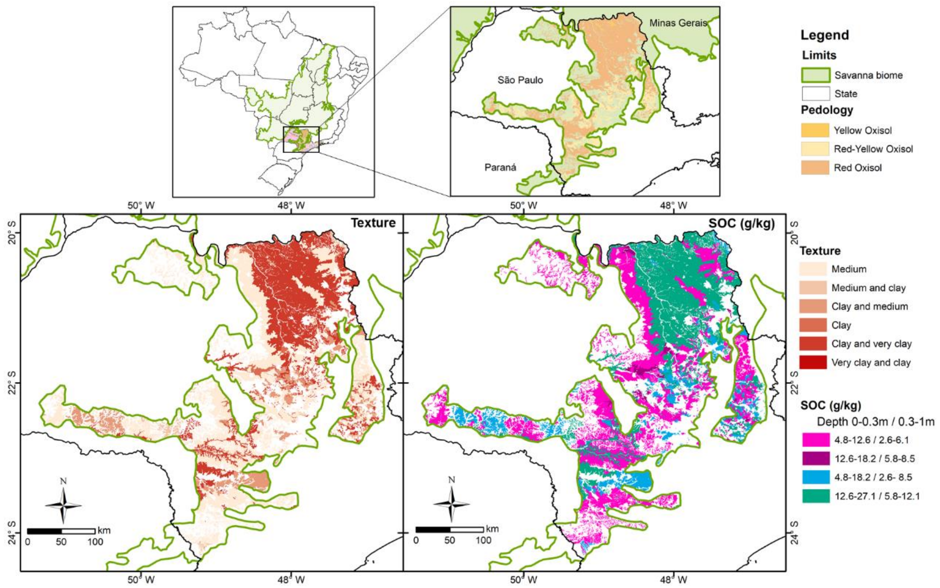

Figure 6. Soil organic carbon distribution in topsoil and subsoil according to the texture.

All results presented so far were restricted to Oxisol order. However, it is an important issue that these models have applicability to other soil orders. Thus, we evaluated eleven different soil orders that occur in São Paulo state, using the same procedure adopted for the Oxisol (Appendix **Figure A4**). The soils of the orders Mollisol and Psamment had an accuracy above 75% for the subsoil and Ultisol an accuracy of 67%. In the case of topsoil, the highest accuracy was 67% for Psamment. These results are only indicative that our models can assist in other soil SOC estimations However, we cannot confirm the SOC models effectiveness for other soils since there is no statistically significant and comparable sampling of soil profiles between soil orders.

4. Discussion

The models were sufficiently validated to prove their merit as a general estimation method or, at least, as a prior trial to the research. We have provided evidence that the models compute the soil organic carbon values close to the real values. This is important mainly to the agricultural regions that do not own a robust soil database or financial resources for large surveys, but they need general mapped data regarding soil quality [37]. The facility to get a notion of the soil carbon in an area where the present status is completely unknown is the greatest strength of these models. Enabling a rough estimation of SOC with only soil texture knowledge means it is possible to work with very low cost in huge areas. According to Vos et al. [38], the soil texture can easily be estimated in the field survey with a relatively high precision using the "finger texturing". However, the models' performance depends on how the variables related to the input data could intervene into the triangle results. We recognize that there are more robust methods [4,39,40], involving other variables that exert influence on SOC and, therefore, resulting in a higher accuracy. Nevertheless, we believe that approach proposed in this work proved to be more than enough for areas where intensive soil survey and analytical effort are not capable of being accomplished.

The precision limits of the models are initially linked to the possible variation of SOC values in short territorial spaces. We found in the analyses a huge textural variation in Oxisols but we expected this result because many other researchers had already reported this fact [4]. However, this variation did not prevent the SOC from being modeled. This outcome is probably due to the strong-positive association between the SOC and clay content [41] and negative association with sand [42] in both studied layers of soil profile [32].

Our data showed more SOC in the topsoil layer than in the subsoil layer, overestimated up to 5 $g \cdot kg^{-1}$, which could be attributed both to the vertical distribution of roots [43–45] and for litter—responsible for up 50% of SOC variations in the levels on the soil surface. Around 62%–79% of the roots in the topsoil layer are concentrated in the first 0.2 m of soil [46], showing an exponential decline of the root biomass and its size according to the dept [47]. Besides the root concentration, the higher SOC values in the topsoil layer also reflect the land use [48] and its management, such as crop residues accumulation left on the top of the land for protection [49]. In addition, it must be considered that SOC amount on the soil surface is related to soil compaction, which would be measured by bulk density [50]. However, the higher carbon concentration in topsoil is not a standard, since other authors reported that the subsoil layer contains as much SOC as the topsoil layer [42,51]. On the other hand, the carbon soil variability in the topsoil of the Oxisols that we have studied is less compared to other researchers [18,52]. Ruggiero et al. [18], for example, reported SOC values from 11.7 up to 26.6 $g{\cdot}kg^{-1}$ in the topsoil and from 6.0 up to 13.7 $g{\cdot}kg^{-1}$ in the subsoil in Savanna region with both Oxisols and Entisols soils. Carvalho et al. [53] also worked with Oxisol in Savanna, describing SOC values from 19.5 to 24.7 $g{\cdot}kg^{-1}$ to topsoil (0.3 m). Then, the models' application must be attentive to the possible margin of error due to these ranges.

When we look at the topsoil and subsoil in greater fractionation of the soil column (**Figure 5** and **Table 4**), we can see the part of the soil that has better performance, which is the middle fraction of both topsoil and subsoil. These results can be influenced by land use-cover which provides different carbon inputs to the soil column. In Brazilian Savanna Oxisols 51% of the area is covered by native vegetation [21]. The vegetation upon these soils displays a mosaic of the structures from savanna-like formations to forest, contributing with different soil carbon input. The planted pasture (27%) was the second land use most presented in Brazilian Savanna Oxisols followed by annual agriculture (15%) and perennial agriculture with sugar cane (5%). The other land use-cover totalizing 2% [21]. Zhang et al. [13], for example, studied SOC profile distribution in 120 samples in native vegetation and agriculture areas, finding a small ranging in native vegetation (5.2 $g{\cdot}kg^{-1}$—topsoil; 3.5 $g{\cdot}kg^{-1}$—subsoil) and a bigger difference in agriculture area (12.0 $g{\cdot}kg^{-1}$—topsoil; 4.9 $g{\cdot}kg^{-1}$—subsoil). However, when we investigated a land portion of Brazilian Savanna Oxisols (Sao Paulo State), the models had better performance in topsoil, probably because the area was smaller which guarantees less environmental variability in terms of climate, relief, and native vegetation cover. According to TerraClass Cerrado [21], in 2013 this region had 46% of its area covered by perennial agriculture with sugar cane, 17% native vegetation cover, and 6% silviculture, with wide homogeneity in its distribution.

In short, the models' users must be aware of how the variables related to the input data could intervene in the punctual SOC or in SOC final map. However, the validation tests concerning the textural triangle both for individual data and SOC map, point to worthwhile practical applicability to be employed.

5. Conclusion

Our results highlight models grounded on soil textural classes that permit to estimate the value of Soil Organic Carbon in Savanna Oxisols. The data can be obtained from two textural triangles, one for topsoil and other for subsoil, based on the equilateral textural triangle. We warn that the models provide better support to SOC-related preliminary research in gross and fast estimates, giving a general notion of potential Soil Organic Carbon and facilitating the empirical study.

Author contributions: Conceptualization, TNT, RACL and RFdS; methodology, TNT; software, TNT; validation, TNT; formal analysis, TNT, RACL and RFdS; investigation, TNT; resources, RACL; data curation, TNT; writing—original draft preparation, TNT; writing—review and editing, TNT and RFdS; visualization, TNT; supervision, RACL and RFdS; project administration, TNT and RACL; funding

acquisition, RACL. All authors have read and agreed to the published version of the manuscript.

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Appendix

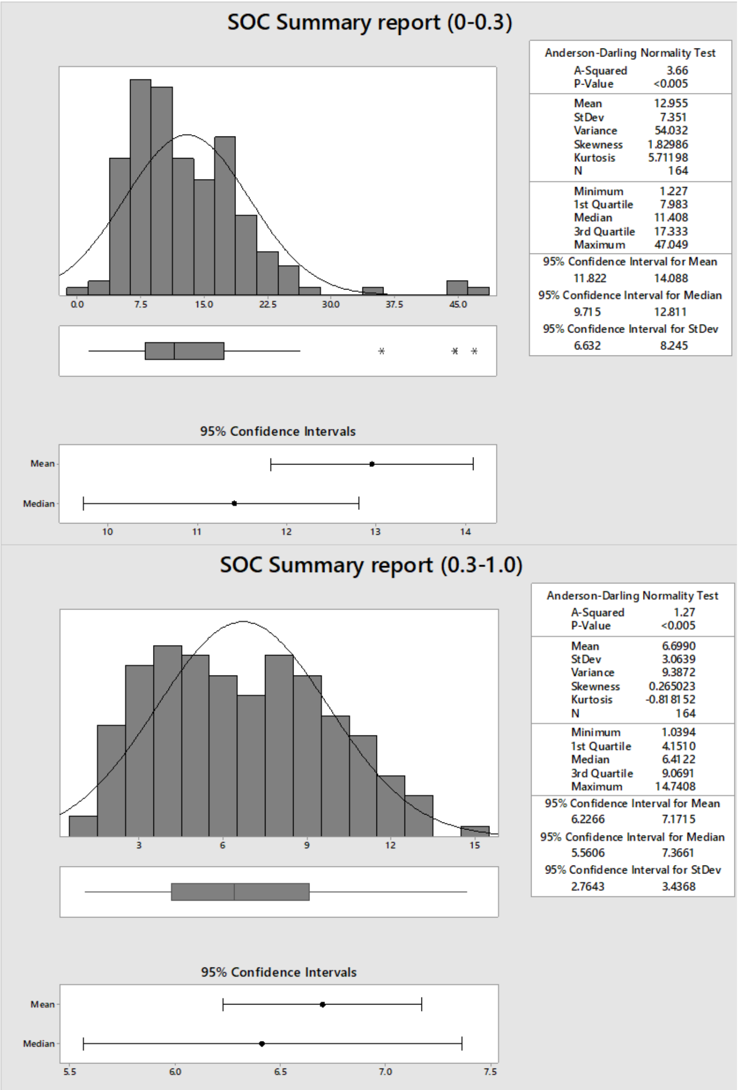

Figure A1. Descriptive analysis of SOC values in the two depth.

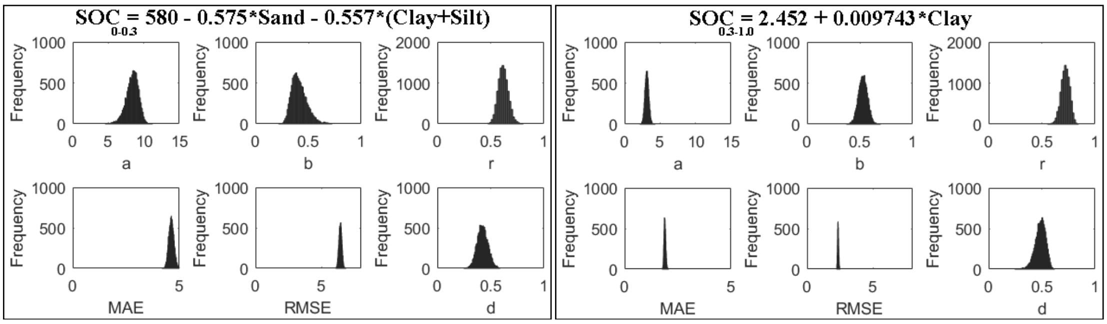

Figure A2. The values estimated by the bootstrap for the best models in the two depths were represented by the histograms above, where (*a*) linear coefficient, (*b*) angular coefficient, (*r*) correlation coefficient, (MAE), (RMSE) and (*d*) statistical parameters.

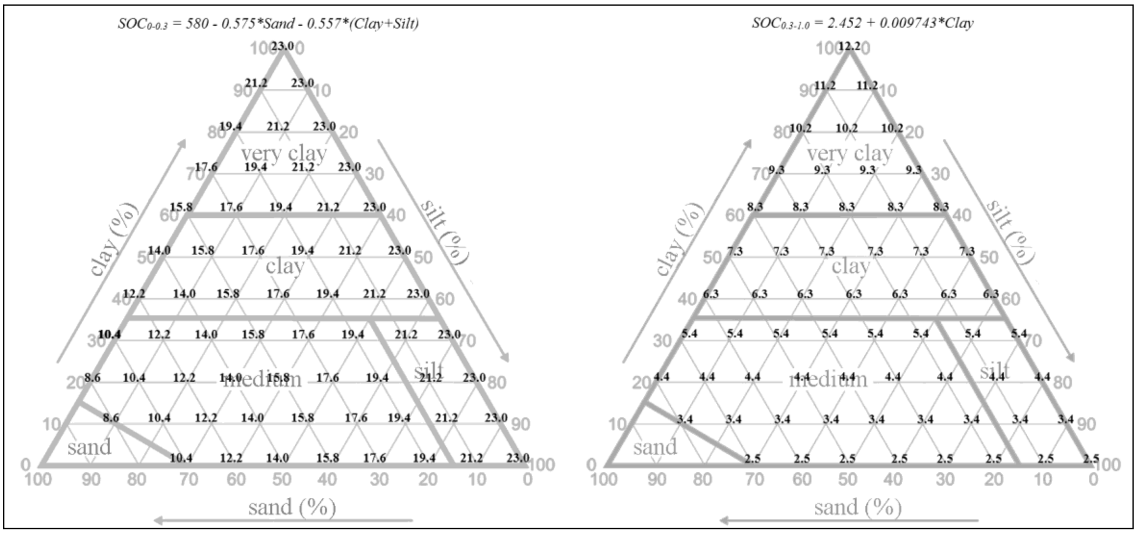

Figure A3. Estimated SOC (g·kg^{-1}) in Savanna Oxisols based on the textural triangle.

Soil order		Alfisol	Aqualf	Histosol	Inceptisol	Mollisol	Nitisol	Oxisol	Psamment	Spodosol	Udalf	Ultisol
0-0.3	N	16	5	3	3	5	30	14	3	2	3	31
(m)	Acurracy	56%	20%	0%	33%	40%	37%	86%	67%	0%	33%	58%
0.3 -1.0	N	20	5	8	2	5	30	40	4	2	5	51
(m)	Acurracy	50%	0%	0%	0%	80%	37%	70%	75%	0%	0%	67%

Figure A4. 287 pedological profile obtained from secondary sources of pedological profiles and ground surveys, between the years 1960 and 2015.

All of them were in São Paulo State. We calculated the percentual concordance between the values presented in pedological profiles and the estimated values by the triangle to the same points as a way of evaluating the models' effectiveness.

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Review

Traditional ecological knowledge and natural resource management: Some examples from Bangladesh

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Abstract: Traditional Ecological Knowledge (TEK) refers to the knowledge, innovations, and practices of indigenous and local communities around the world. As it includes proven technologies for particular situations, its adoption cuts research costs and time. This paper attempts to find out the scoping of some TEKs on different practices ranging from plain land agriculture, hill farming, agro-biodiversity management, open water fish conservation, disaster management, and other aspects in different situations in Bangladesh. It is an outcome of the authors' field experiences in the study of local flora, plant uses, and natural resource management practices in the community and a review of related literature. Access to modern facilities, urbanization, and land use changes are now causing many threats to TEK. Documentation and codification of this knowledge and its uses for sustainable development are needed for the betterment of local farmers as well as the preservation of cultural heritage. The knowledge is always changing to cope with socio-cultural needs. So, a fusion of TEK and modern scientific knowledge can help solve the problems encountered in the sustainable management of natural resources. It also needs to be incorporated into school curricula and mainstreamed in the local-level natural resource management planning process. The best practices can also be adopted in natural resource management.

Keywords: biodiversity; sustainable development; indigenous knowledge; local knowledge; traditional knowledge

1. Introduction

Traditional usually refers to "cultural continuity transmitted in social attitudes, beliefs, principles, and conventions of behavior and practice derived from historical experience" [1]. Ecological means related to ecology, meaning the relationship between living beings and their environment. Knowledge is the facts, information, and skills acquired through experience or education; it is the theoretical or practical understanding of a subject. According to Levin [2], TEK is a cumulative effect of the knowledge, practice, and belief of the people, which evolves through adaptive processes and is transmitted through generations. Thus, it is a holistic system of knowledge, practice, and belief complex in a society [2,3]. It is a continuation of the resource-use system of a particular land. It is also designated as a subset of indigenous knowledge, generally unique to a given culture or society. Local and indigenous knowledge is often used synonymously for the skills and wisdom of local communities developed through interactions with their natural surroundings [2].

A review by Mathias [4] gives the conservational aspects, merits, methodologies, and usefulness of TEK in sustainable resource management. Though the importance of the TEK is recognized for natural resource management, this knowledge system is now in danger of erosion due to rapidly changing environments and reckless shifting economic, political, and cultural phenomena from a global standpoint [5]. For the sake of biodiversity conservation, food security, and the protection of the world's natural resources, TEKs need to be preserved, revived, and integrated into mainstream planning [6].

Article 8 (j) of the Convention on Biological Diversity (CBD) calls for the conservation of traditional knowledge. Promoting TEK can also help achieve the Sustainable Development Goals (SDGs). TK is sometimes linked with the culture and diversity of a society [7,8] and is environmentally and socially appropriate and sustainable [9]. Subramanian and Pisupati [10] highlight the significance, opportunities, and challenges of sector- or system-wise adoption of traditional knowledge, their adaptive capacities (environment management and climate adaptation), governance processes, ethics and equity, and the process of mainstreaming TEK in the sectoral planning process. Recently, Rai and Misra [11] presented a nice compendium on the concept, practices, and issues of TEK in the realm of indigenous natural resource management techniques in Asia.

Most TEK reports from Bangladesh include ethno-botanical studies and are mostly on food and medicinal plants. There are a wide variety of underutilized food plants in Bangladesh [12–14]. The majority of reports on the traditional use of plants are from the Chittagong Hill Tracts (CHTs) region. The recording of TEKs from CHTs dates back to Lewin [15]. A good number of reports also exist on the scope of integration of TEK in different farming subsystems like agriculture, fisheries, non-wood forest products, and sand disaster management in Bangladesh under different agro-ecological and socioeconomic environments [16–29]. TEK is to some extent used for local decision-making processes in a variety of fields, including plain land agriculture, hill farming systems, fisheries and freshwater ecosystems, and disaster and climate forecasting in Bangladesh. This study focuses only on the importance of TEK in managing natural resources.

2. Methodology

The article is mainly based on author's experiences from field observations documented on different traditional practices and innovations of different farmers' communities from Bangladesh recorded over four decades. The author also used the information from secondary sources through literature review.

3. Documented TEKs

3.1. Plain land agriculture

3.1.1. Homestead an integrated farming system

Homesteads are unique ecosystems of rural Bangladesh. Human settlements throughout most of Bangladesh are mostly in villages which comprise both dwelling houses and other production farming components like vegetables production, fruit production, tree production, poultry, livestock, even small shops, processed foods and even cottage based manufacturing units. The plant based production system presents a prototype of a typical tropical multi-layered forest. Interacting with nature people from rural Bangladesh over time have acquired knowledge on land use, site specific species selection, their cultivation, utilization, management, conservation and value added product development.

3.1.2. Integrated pest management

Farmers encourage and facilitate birds sitting for preying insects in paddy fields. They put bamboo sticks, brush woods of trees in rice fields for landing and sitting of insect preying birds; spraying neem leaves solution to control insects on vegetables, dusting tobacco powders to control insects, dusting ash to cucurbit vegetables to check aphid attacks, intercropping of garlic and potato to minimize pest infestation, etc. [27].

3.2. Hill farming

About thirteen ethnic communities live in Chittagong Hill Tracts (CHT [30] and have their own traditional knowledge. The member of hill communities in the CHT developed different location and community specific farming practices. Shifting cultivation locally known as jhum is the main cultivation practice in the CHTs. Following are some TEKs relating to hill farming practices in the CHTs.

3.2.1. Land use zoning

Generally, hill people consider land type, topography, hill slope gradation, aspects, soil texture etc. for making use of land for agriculture and production purposes. These local knowledge based landuse plans are ecologically and socially very sound. They follow some sorts of zoning for land use planning. The broadly classify land types into three land use categories as given in **Table 1**. In addition to these they also use the streams and water courses (jhuris and charas) for multiple purposes.

Table 1. Land use classification practices by four hill communities in the CHT.

Zoning categories	Marma	Murang	Tanchangya	Bwam	Characteristics
Villages or Para	*Rowa*	*Kowa*	*Aram*	*Kuwa*	Villages comprise cluster of houses
Farming sites or *Jhum*	*Yah*	*Yowa*	*JhumJa*	*Laow*	Main cultivation on the hill slopes
Fallow *jhums* or *Raiyna*	*Ran Min song, Wang MiWah*	*RainyaJa, Ja Bhui, Tarong*	*Reserve or Kowa reserve*	*Reserve*	Kept undisturbed after *jhum* and again used for *jhum* after few years

3.2.2. Indicators for *Jhum* land selection

The shifting cultivation, locally termed as *jhum* is the major farming practice in CHTs. It is a slash and burn system mostly practiced in hill slopes. It provides major crops for the sustenance livelihood of the hill people. Generally, people follow following in selecting a jhum site:

- gentle slopes (generally the middle portion) are more preferred to the steep slopes;
- bamboo vegetated lands;
- lands covered with *kurjuklota* (*Mucuna* spp.);
- the area covered with *ramkola* (wild banana) is supposed to be suitable for chili cultivation; farmers think that the banana ashes enhance chili production in the *jhum*;
- loose textured soils with no gravel or least gravels;

- soils with earthworm burrows and colonies.

Farmers prefer a little admixture of gravel in soil in selecting land for fruit orchard establishment. Hills consisting of sandy loamy soils are considered as good site for village establishment. Sandy loam texture provides perennial seepage water to the streams. Thus, most of the hill villages are established along the streams.

3.2.3. Periodical sowing of seeds in *jhums*

Considering the harvest time, seed size and other managent needs the farmers follow some periodic sequence in seed sowing in *jhum* field. Generally they sow seeds in three stages in the *jhums.* Generally, in *jhums* seeds are dibbled in small holes. But crops with small seeds (*Ocimum*, *Capsicum*, *Coriander*, etc.) are broadcasted all over the field as soon as fields are cleared and ready for sowing. Seeds of rice, cotton, maize and other vegetable crops by dibbled after a week of first broadcasting. When the rice seedlings attain about four inches in height, farmers broadcast *til* (*Sesamum indicum*) seeds. It is reported that if the *til* seeds are sown with rice it hinders the growth of the rice tillers. This is a system to avoid allelopathy of sesamum-rice interaction at germinating stage.

3.2.4. Knowledge on local climate condition for climate resilient crop selection

Climate is an important parameter for selecting crops for a particular area. The *Murang* community of Empu Para, Bandarban district had selected crops for the area based on local climatic conditions. At high altitudes the night temperature is cool. This climatic condition is locally called as *thanda* (coldness). Climate at lower elevation climate is a bit hotter and locally called *gorom* (warmness). The farmers of Empu Para at a higher altitude in Chimbuk hill range (about 875 m) grow citrus fruits like orange (*Citrus reticulata*), malta (*Citrus sinensis*), jambura (*Citrus grandis*), and satkora (*Citrus macroptera*) etc. in addition to *jhum* farming.

Empu Para is situated at higher elevation than Bandarban and Ruma. The night temperature is comparatively cooler in Empu Para and this condition is locally called as *thanda* and considered as suitable sites for citrus cultivation and not suitable for ginger cultivation. Foggy weather during flowering time is considered to be suitable for good citrus fruit setting. On the other hand, Sharon Para is comparatively hotter (*gorom*) than Empupara, and, considered suitable for ginger cultivation. Climate is considered comparatively warmer (*gorom*) in Ruma and Bandarban than Empu Para, and farmers grow here pineapples, mango, banana, *lichi, boroi* and *papaya*. This knowledge can play important roles in selecting climate resilient crop selection [23].

3.2.5. Altitude and wind velocity in selecting crops

Altitude and wind velocity are considered important in selecting crops. The farmers at high altitudes do not cultivate *til* (*Sesamum indicum*) in *jhum*, because when the *til* fruits ripen, the pods split up and disperse seeds for high wind velocity. This is an important criterion for crop selection where altitude is a factor [23].

3.2.6. Broad zoning of hill Slopes for different crop cultivation

Slope gradation is an important factor in hill cultivation. Generally, the foot hills or base of the hills are rich in moisture content and nutrients. Local people have knowledge about slope situations and species suitability along different slope gradients. Crops of different habits such as annual crops (like aroids, gingers) are planted towards the lower slopes and foothills. Mid-slopes are preferred for fruit trees. Toward the hilltop people generally plant timber trees.

3.2.7. Insect repellent barriers by cultivation of ornamental plants along the periphery of *jhum* fields

Hill farmers plant some showy ornamental flowering plants particularly of Asterace family along the periphery of *jhum* field for beautification. Mostly merry gold, coxcomb and cosmos flowers are planted. It is a belief of farmers that pungent smell of ginger, onion, mint and pepper and bright flower colour work as an insect repellant. It could be a good biological pest control approach. This practice will help to reduce insect attack at field with any use of insecticides and pesticides.

3.2.8. Indigenous seed collection process

Local seed collection is simple and hygienic. Farmers prefer to collect seeds from disease free mother source. Generally, people select healthy mother plants and collect mature and bigger sized fruits from them. In case of upland paddy farmers harvest the desired crops in a sunny day thresh them immediately after harvests. For fleshy big fruits like gourds farmers put some rice straw beneath the fruit in the field, so the they do not touch the soil. Farmers dry extracted processed seeds in sun for 7–10 days and store them in bamboo potsor hallow gourd pots. To protect seeds from insect attack and maintain optimum levels, seed jars are stored near fire place or hung under roof over stoves. This is how the hill people maintain the local germplasms of different crops [26].

3.2.9. Traditional seed storage techniques

Almost all hill farmers from different tribes follow similar seed storage systems in the CHTs. Traditional seed storage techniques practiced in the CHTs are given in **Table 2**. This is an economic and sustainable system of seed management for the hill areas.

Table 2. Indigenous crops storage process practiced by hill people of CHT.

Seeds types	Indigenous storage process
Paddy	Stored in bamboo made baskets locally called *turong*. Seeds are covered with dried leaves of banana (*Musa* sp.), teak (*Tectona grandis*), moos (*Pterospermumacerifolium*) or palm (*Caryota* sp.) to maintain moisture.
Cucurbits seeds	Washed thoroughly with water and sun dried for seven to ten days and stored in locally made bamboo small baskets (*Turong*).
Other Vegetable seeds	Stored in earthen pots or in *toyea* (*hard shell of gourd*) and keep them in a warm dry place usually attached with the kitchen wall.
Maize seeds	5−10 bunches are knotted together and kept hanging from kitchen roof to keep seeds viable and free from insect and fungal attack.
Ladies finger, Borboti (bean)	Tide up together and kept hanging from roof of kitchen roof to avoid insect and fungal attack.
Tulsi (*Ocimum* sp.)	The whole plant is dried and kept beneath the house roof.
Root crops	Tubers or roots are stored in dry places covering with soils near their house. Aroids stored in field or in bamboo basket (*Turong*) covered with grass and placed in shade near their house.

3.2.10. Conservation of germplasm through seed distribution

A community based traditional seed sharing system still exists among the *Marma* peasants in the CHT, more than ten local upland varieties of rice are cultivated in the hills of CHT. Each family generally maintains germplams for 3–4 varieties. Farmers exchange among themselves the different varieties as they desire to plant. This community-based seed sharing system had been an effective method of maintaining agro-biodiversity over time and localities. This also helps in maintaining community and reduced the storage risk.

3.2.11. Indigenous nursery method for citrus

Orange and pumelo are two important cash crop for income generation to the *Murang* community in Empu Para. The hill farmers have developed indigenous method nursery rising for citrus seedlings. They raise citrus seedlings in bamboo baskets. An abandoned bamboo basket is filled with soil, or a bamboo platform layered with soil is made at about one meter above the ground. Seeds are sown in the baskets or into soil layers on platforms. The seeds germinate in the baskets and soil beds in bamboo platform. After one year the seedlings are pricked out and transplanted in the seedbeds in the field. The perception behind this practice is to keep the seedbed away from the disturbances of poultry birds, pigs and to easy nursing the seedlings. When the seedlings attain about one meter height, bare-rooted seedlings are planted in the field during the monsoon. In this practices, local resources based biodegradable containers are used and thus it environmental friendly and economic [26].

3.2.12. Ginger field management through mulching

Ginger is a cash crop in the CHT-hill farming system. It is a practice of the hill people in the CHT to mulch the ginger field after sowing. Hill farmers use to mulch ginger fields with brush wood harvested from fallows. But they prefer to mulch with old thatching grass (*Imperata cylindrica*) abandoned from thatched roofs. The abandoned thatched grass decomposes at a slower rate than brush wood. This practice suppresses grass and other weeds, and increases the soil temperature that helps ginger in emerging shoots. Mulching material in the long run decomposes and adds humus to the soil.

3.2.13. Indigenous ginger storage method by the *Bwam* community

Ginger is an annual crop growing important spice with good market potential all over the country. It cannot be stored in open condition for longer period after harvesting. Storing of ginger for longer period can bring better price to the farmers. But there are no modern storage facilities for ginger storing in the hill areas of Bandarban. So, innovated *Bwam* farmers of Sharon para, Bandarban have developed Indigenous ginger storing method, which help them to enhance their income. In this method farmers store ginger in large pits dug in the soil. To store ginger the farmers dig large rectangular shaped pits near their houses. They make a sand layer at the pit floor and put fresh gingers on the sand layer. Then spread a layer of hay, rice straw or other dry grasses over the ginger and cover with soil. A shed of thatched roof is made over the pit and a drain is made around the pit to protect it from the rainwater. This system does not any additional space and capital investment. Thus, it is economic method to maintain soil moisture and to reduce the soil erosion [26].

3.2.14. Silvicultural management of trees in the *jhum* field by the *Murang* community

During preparation of jhum field farmers generally slash and burn the existing woody l vegetation from the site. But the Murung community members in Empu Para keep some important trees like *Albizia* spp., *Derris robusta* and other leguminous trees and *Ficus* spp during field preparation. When they fell trees they cut them at about one-meter height above the ground so that browsing animals cannot reach coppiced shoot at this height. The newly produced shoots become susceptible to wind break. Many *Murangjhumias* of Empupara lop the branches of the retained trees for easy light penetration in the ground. This is some sort of aidded natural regeneration process towards restoration of ecosystems.

3.2.15. Indigenous knowledge for mushroom identification

Mushroom is delicious food to hill people and locally called *ul* or *ulli* (Chakma) with potentials in local markets. Wild mushroom naturally grows in the forests and the hill people have knowledge of differentiating edible from the poisonous ones. The clump forming mushrooms growing on dead logs, bamboo culms and soil are considered as edible. On the contrary non-clump forming mushrooms are considered poisonous. Sometimes the hill people do hydrated quicklime test to determine edibility of mushrooms. Hydrated quicklime is applied on the fruit body of the mushroom. If lime applied area becomes black then it is considered as poisonous. The mushroom covered with the ants is considered as edible by the *Tanchangya* tribe. The mushroom growing on logs of *dharmara* (*Sterospermum personatum*) and *gamar* (*Gmelina arborea*) are considered as edible. In *Chakma* and *Tanchangya* language the the mushroom is called *ul.* A folk classification of edible mushroom by the *Tanchangya* community [23] is given below.

- *Thompuul*: Clump forming mushroom growing on the soil.
- *Bas ul:* Large mushroom on soil, sweet in taste.
- *Kala ul:* Mushroom that grow on the debris of Banana.
- *Thiniaul:* Red mushroom that grows on decade wood along the streams.

3.2.16. Gamar coppice management

Gamar (*Gmelina arborea*) is a fast-growing timber tree species planted in private forestland. Indigenous people have developed a coppice management system for *gamar.* Felling cycle has been fixed for 10–12 years cycle. The timber is harvested during dry months and cut at about 15 cm above the ground level. The stumps are protected from browsing. Profuse coppice shoots develop from stumps within 15–30 days. Selected coppice shoots are retained and managed for next rotation.

3.3. Ecosystem services and management

3.3.1. Management of catchments areas

Traditionally the local people manage and maintain catchment areas. While preparing jhum fields they maintain vegetation cover at the upper catchments without any disturbance of the vegetation what ensures continuous flow of stream water. Even when they prepare *jhum* land they keep a strip of vegetated land along the foothills to protect soils from erosion and adjacent land from *jhum* fire.

3.3.2. Stream banks protection

To protect canal banks from erosion and conserve soil water hill people plant a bamboo locally called *baijja bans* (*Bambusa vulgaris*) along the canal banks.

3.3.3. Seasonal cross dam and small scale irrigation

To irrigate downstream agricultural fields the hill people in the CHTs make earthen cross dam across the streams, which is locally called *Goda*. In addition to irrigation local people use this water for domestic purpose.

3.3.4. Water harvesting ditches

Seepage water harvest for domestic purposes is a traditional system in hill of CHTs. The seepage water flows downward through narrow channels (locally called *jhiris*). People dug small rectangular shaped ditches at the base of the hills for reserving seepage water and the excess water is let out through a small hole. For steady supply of seepage water in the streams the vegetation at hill top is kept intact and nobody is allowed to harvest any timbers and fuel wood form the area.

3.4. Yam harvest by forest dwellers in mid land Sal forests

3.4.1. Regulated wild yam harvest by the *Mandi* community

The *Mandis*, a forest dwelling community in mid-land *sal* forest of the country depend to some extent wild food plants during the months of November to February. During this period, they generally collect wild yams from forests. They dig out yams removing soils around the tubers by shovel or spade. While harvesting people cut the yam tuber keeping few centimeters of yam below the collar zone and the basal part of the stem. Then, the dugout whole is again filled with soils where the new yam tuber develops. Soil works during digging process make soils loose that make space for development of new yam tubers. It is learnt from the people that if the matured yam tuber is not collected then it is rotten under the soil. This harvesting practice is a sustainable mode of production and consumption.

3.4.2. Yam processing by the *Santals*

Sliced yams are kept in running water in the stream overnight to wash away of bitterness.

3.5. Tree based agroforestry in mixed evergreen forests

3.5.1. Betel leaf farming by *Khasi* communities

Betel-leaf (*Piper betel*) cultivation using forest trees as support is a cash-oriented agroforestry system by the *Khasi* communities in north-east forest areas of the country. Existence of a good density of standing tress is an important criterion in selecting a farm site. Generally, the betel-leaf growers do not extract any standing tree from the farm stand, but further allow seedling to grow. From their experience they maintain a tree density per unit area. Thus, this production system plays an important role in biodiversity conservation, particularly of tree diversity. A study by Haider et al. [31] recorded 86 plant species in *Khasia* betel-leaf farms as support tree. Stocking density of trees in farmland is 1452 trees per hectare excluding seedlings and saplings, with a wide variety of diameter classes.

3.5.2. Bio-safety measures: quarantine against *Utram* disease (leaf rotting by *Phytophora* sp.) in Khasi betel-leaf farm

No outsider is allowed in to the farm. Keep water at access gate to wash limbs while enters in to the farm. After getting back clothing are washed with a shower.

3.6. Floating agriculture

Floating agriculture (*Dhap*/*baira*)

Farmers' innovative practice growing vegetables on floating rafts is a traditional system in Southern floodplains of Bangladesh (Barisal, Goplaganj and Pirojpur districts). This floating garden is locally known as *Dhap*/*baira*. Farmers construct floating platforms or rafts of reasonable size with local hydrophytic resources like water hyacinth (*Eichhornia crassipes)* and other aquatic weeds and cover with soils. They sow seeds of different vegetables on this soil bed [29]. This is an adaptation to water level rise due to climate change. Different development agencies and the government of Bangladesh have been promoting it in other parts of the country. Department of Agriculture is extending it for rice seed bed preparation in flood affected areas.

3.7. Fisheries

3.7.1. Traditional fish sanctuaries: *Kata*/*Kua*

This is a temporary fish park set in freshwater wet land in the country for preserving fish seasonally in a particular area. People can identify the right site of fish assemblage of fish and demarcate the area by putting bamboo posts. Then they put brush wood piles in that area for fish conservation. In most of the areas this is locally called *kata* or *kua*. This is a good mode of fish conservation. In the past decades this has been linked at project level and many fish sanctuaries have been established throughout open water ecosystem in the country. Farmers have knowledge about brushwood species, like: *Streblus asper, Tamarindus indica, Pongamia pinnata, Barringtonia acutangula* etc. [25].

3.7.2. Small scale rice-fish production

This is a traditional system practiced in many parts of Bangladesh. In this traditional culture system farmers generally dig several small ditches in the rice fields and put tree branches or bushes to make artificial habitat to attract wild fishes [24].

3.8. Disaster management

3.8.1. Traditional homestead protection from wave erosion (*tafal*) in haor areas

Bamboo pole fences tied with strings against soil mounds in angels leaving space between the bamboo fence and the soil mound. The gap is filled up with *chilla* grass that does not rot under submerged condition. It is locally called *Aar Bandha* and also called *chailla deoa*. Community labors are involved and based on local resources [29].

3.9. Food processing and preservation

3.9.1. Indigenous food preservation through sun drying

Consumption of dry fish is part of food culture in many parts of Bangladesh. People have the practice of fish preservation through sun drying. The dry fish is a commercial commodity in Bangladesh and it ensures protein security in lean natural fishing periods. In many open water fisheries areas it is a conventional practice and a commercial enterprise.

In hill areas vegetables preservation through sun drying is a common traditional system. Generally, women process many vegetables and foods like radish, bamboo shoots through slicing sundry them to preserve for the rainy season [32]. Storage and preservation of many fruits like jujube, tamarind and many medicinal herbs are also practiced. This ensures food security and cash generation during lean periods.

3.9.2. Salting of hilsha fish

There is tradition of preserving sliced *hilsha* fish by salt in many parts of the country.

3.9.3. Pickles

Preserving fruits as pickles in different ways is an age-old practice in Bangladesh. Generally, fruits are preserved as pickles in brines or thick sugar syrups or in mustard oils [33].

4. Discussions

It is evident from the review that in Bangladesh many TEKs are still use in practice in production systems like agriculture, tree production, fisheries, livestock, disaster management etc. These all ensures food security, health care, livelihoods and climate change vulnerabilities. TEKs described here are limited to some locality specific production systems. TEKs from many other production systems and commodities are not described or recorded. Most of the practices are locality specific. Never the less, people from different parts of Bangladesh are still practicing indigenous methods and these have different degrees of positive impacts on natural resources management. The practices are centered on ecosystems, their services, biological resources (both plants and animals), their uses, value addition processes and conservation. In totality a management system is operative in the ecosystems and their components.

TEK is now shrinking at an alarming rate due to urbanization, market influence, population increase, land use changes, out migration of young generation to urban areas, access to the modern facilities and overall reluctance of the young generation for this un-codified knowledge system. The United Nations has declared the decade 2021–2030 as *UN Decade of Ecosystem Restoration* (2021–2030) to halt and reverse the degrading ecosystem of the world. Practicing TEKs are milestones towards achieving the declaration. These TEKs play direct roles in achieving *Sustainable Development Goal 15* and also other crosscutting issues. At the 2016 The World Conservation Congress in 2016 adopted a resolution (WCC-2016-Res-069) which, for the first time, defined the use of nature for simultaneous benefits to biodiversity and human well-being as *Nature-based Solutions (NbS).* The practicing TEKs are in fact the existing *NbS* towards conservation of nature and biodiversity. Thus, the practice of TEKs is playing active roles in meeting the demands of these global development agenda.

5. Conclusion

TEKs being informal are transferred orally from generation to generation and not codified under any formal discipline. Information so far recorded is fragmentary. To make use of this knowledge system the practices are need to be kept viable. Also, the lost ones need to be revived. It needs a collaborative effort so that it does not get further lost and to make it perpetuated. UNESCO's Local and Indigenous Knowledge Systems programme (LINKS) promotes local and indigenous knowledge and its inclusion in global climate science and policy processes. LINKS strives to strengthen indigenous peoples and local communities, foster trans-disciplinary engagements with scientists and policy-makers and pilot novel methodologies to further understandings of climate change impacts, adaptation and mitigation [34].

Our young generations need to be enlightened with this knowledge system. So we need to incorporate this knowledge system into school curricula. In addition, universities and research organizations should collaborate with governments to systematically collect codify and document all forms of TEK for the current and future generations. These could be adopted in local development planning process. Furthermore, these attributes need to be mainstreamed in developing local level natural resource utilization and management plan. One of the approaches could be adoption of best practices [10].

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Review

Methods for economic assessment of forest resource degradation: A systematic review

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Abstract: Forest degradation is one of the challenges facing the planet today. Several methods have been used to measure forest degradation, including spatiotemporal model analysis, satellite analysis, remote sensing, time series data, geospatial techniques, and most recently aerial drone imagery. However, few studies have used economic valuation methods to assess forest degradation. Therefore, this research aimed to identify the methods used the economic assessment of forest degradation. This systematic review was carried out using PRISMA guidelines. Research articles on the economic valuation of forest resource loss, published from 2015 to 2022, were electronically collected from three databases. Three independent reviewers, with the third acting as referee, inventoried articles, extracted data, and assessed the risk of bias in the articles included in the study. A total of 10,095 articles were identified, including one article from the grey literature. Only five articles met the eligibility criteria. A qualitative content analysis was performed on the extracted data. The selected articles used various methods. However, only a few articles used the contingent valuation method, even though this is indicated for estimating the highest economic value of forests. Based on forest functions, the articles evaluated erosion due to the absence of trees, wood loss, recreation areas and externalities due to forest loss, air quality, water regulation, food supply, and wildlife. The main limitation of this review was the small number of studies included, which may have affected the findings. The study protocol is registered in PROSPERO under the number CRD42021223242

Keywords: economic assessment; deforestation; contingent valuation; natural resources; PRISMA

1. Introduction

Global forests provide a multitude of ecosystem services (ES) for human well-being [1,2]. Conservation of the forest ecosystem is fundamental to economic and ecological sustainability [3]. In fact, local livelihoods depend on forest resources. Therefore, sustainable use of forest resources contributes to improving local incomes, hence the need to make its exploitation sustainable. Forests, in general, and tropical forests, in particular, play a vital and well-known role due to the ESs they provide [4]. Unfortunately, these valuable natural resources face many threats, especially deforestation and forest degradation [5–7]. However, there are different definitions of these two threats in the literature. Therefore, we define deforestation as a decrease in the area covered by a forest, and forest degradation as not only a reduction in the area of the forest but also a decrease in the ESs it provides. In this study, we did not consider the difference between these two terminologies. Therefore, it is clear that healthy forests are at risk, in the context of global changes, from increasing temperatures and extreme climatic events [8]. Ecosystem degradation and biodiversity loss affect the proper functioning and resilience of ecosystems and, thus, threaten their capacity to provide a continuous flow of ESs to present and future generations [9]. Around the world, deforestation is a problem [10], and much of the loss of global biodiversity and other ESs results from human-induced degradation and deforestation [11]. The UN has set environmental targets, urging action to combat climate change and its repercussions (Sustainable Development Goal 13), even though these targets are negatively impacted by the creation of strong institutions and economic growth [12].

Several studies have focused on the measurement of forest degradation around the world. For example, Borges et al. [13] used time series data to assess forest loss in Tanzania and Eastwood et al. [14] used similar data to identify the causes of ecosystem function loss and predict the future of ESs under different climate and pollution scenarios. The natural resource to which this study applied was the watershed. One study in Mexico used economic valuation to measure the loss of coastal ESs [15]. An economic approach was applied to coastal ecosystems, which are not exactly forest resources. Furthermore, Hiltner et al. [16] focused on the importance of forest condition in estimating biomass losses from tropical forests. The method used was based on an analysis of tree loss detection in forest areas using a time series of aerial images acquired by drone. Similarly, Ouattara et al. [17] used aerial images taken by drones to detect the loss of forest trees in Côte d'Ivoire. Another study performed a global meta-analysis using dung beetles as indicator taxa [18]. This meta-analysis looked at how the loss and degradation of primary forests reduced biodiversity and ecosystem functioning. Although this study focused on forests, dung beetles were used as indicators because of their sensitivity to anthropogenic disturbance and their importance in performing essential ecological functions in terrestrial ecosystems. Another study used spatio-temporal dynamics analysis using Landsat images and a supervised random forest classifier to measure the transformation of rural landscapes in the Vietnamese Mekong Delta [19]. Finally, Sugimoto et al. [20] used scattering power decomposition and optimal averaging of volume scattering power in tropical rainforest regions to assess deforestation.

One observation about these studies is that either the resource being evaluated was not a forest or the methodology used was not an economic valuation. Most of these studies used spatiotemporal model analyses, satellite, remote sensing, time series data, and geospatial techniques as assessment methods [21–27]. However, few works have used economic valuation methods to assess forest degradation.

Monetary valuation of biodiversity has a triple benefit: it informs decisions that maximize well-being, provides a means to set trading targets, and is effective in attracting the attention of policymakers [28]. Estimates of economic costs and benefits of land-use options can inform decision making about the multiple benefits that biodiversity and ecosystems provide to human well-being as well as about the economic consequences of ecosystem loss [29]. Moreover, systematic reviews focusing on the economic valuation of forest degradation are few in number despite a revival of this method in recent decades [2]. The study by Förster et al. [30], which is the only systematic review to allude to cost assessment, covered all ESs. Thus, to our knowledge, there has been no systematic review that deals with an economic valuation exclusively on forest loss. Therefore, our study used the Preferred Reporting Items for

Systematic Reviews and Meta-Analyses (PRISMA) guidelines to perform an economic valuation of forest clearance. We have identified the latest studies in the field from around the world, which is the contribution of our research.

Systematic reviews and meta-analyses are essential tools for summarizing evidence in an accurate and reliable manner [31]. A systematic review of the literature is a qualitative research method that aims to gather all empirical evidence meeting predefined eligibility criteria to answer specific research questions [32]. It provides knowledge from multiple articles. Thus, a systematic review can give an in-depth global view of a research question. A systematic review of economic valuation includes the determination of the utilitarian concept of value, incorporating ethical and social dimensions [33], and a consideration of use and non-use values [2]. Economic valuation takes into account sustainability and social and environmental aspects. Therefore, economic valuation can play an important role in guiding optimal decision making and correcting imbalances between environmental management and economic development [34], particularly because policymakers are more sensitive to economic data.

This study aimed to identify how researchers assess the economic value of forest degradation. A systematic review generally follows a four-step process: identification, review, eligibility, and inclusion [31]. Specifically, this involves i) identifying studies in the selected research databases and eliminating duplicates, ii) examining identified studies on the basis of titles and abstracts, iii) selecting articles after evaluation of the full texts, and iv) selecting those that meet all the eligibility criteria. The study was indifferent to the populations chosen because these depend on the economic method used, and it did not make a comparison between groups (treated and untreated). All types of economic valuation studies were considered, but the included studies were based on the economic valuation of the loss of natural or related resources. Preference was given to deforestation. We conducted searches of three databases from November 2020 to September 2021 and updated in February 2023. The extracted data were the full references of the included studies, their methodology, and their main findings. All this information will be described in a narrative.

2. Materials and methods

2.1. Protocol and registration

This systematic review was registered in PROSPERO as CRD42021223242. The practice of systematic review is used in several disciplines, including environmental conservation and management [35,36]. Here, it will be applied to the assessment of forest degradation. We used the PRISMA guidelines [31] through its four steps: identification, review, eligibility, and inclusion (articles included in the study).

2.2. Eligibility criteria

Searches were conducted from November 2020 to September 2021 and updated in February 2023 for articles on the economic valuation of natural resource loss, particularly forests. The identified articles have been published in all languages as of 2015. To answer the research question of how researchers estimate the economic value of forest degradation, the population, intervention, comparison, outcome/output, study design (PICOS) approach was used to identify the eligibility criteria (**Table 1**).

Table 1. Population, intervention, comparison, outcome/output, study design (PICOS).

Category	Results
Population	Population selected to assess the loss of natural resources
Intervention	Any type of study on economic valuation
Comparison	The study will not make a comparison between groups (treated vs. untreated)
Outcome/output	Full reference study (author names, country, study identity and publication year, document type, journal), methodology (valuation method, sample size, sample characteristics, model, settings, area of study site, location, year of valuation, underlying assumptions), monetary value (minimum, mean, median, maximum), valuation (type of prospective assessment or retrospective evaluation, type of natural resources assessed, nature of valuation)
Study design	The studies included were those based on an economic valuation of the loss of natural resources. Preference was given to deforestation

2.3. Data source

Articles were selected electronically from three different databases: Web of Science, Scopus, and Environment Index. Keywords were searched in the article title, abstract, and subjects. These keywords were ("economic valuation" OR "economic analysis" OR "economic assessment") AND ("deforestation" OR "forest degradation" OR "natural resources loss" OR "forest loss"). In addition, reports of congresses or conferences dealing with the subject were used. References from the included articles were also used. At the end of this step, several articles were identified.

2.4. Study selection

Two independent reviewers evaluated all the identified articles. Discrepancies were discussed, and a third reviewer acted as an arbitrator in case of non-consensus. The identified articles were exported to Zotero and to the Colandr application. Duplicates were eliminated. The next step was to review the titles and abstracts. Articles on irrelevant topics were rejected. Then, the full texts of the articles were carefully reviewed to select eligible articles. The included articles were those whose methodology and nature of the natural resources (in this case, forests) were deemed to be consistent. Descriptive statistics were used to access the data.

2.5. Data extraction

The two independent reviewers extracted relevant data from all included articles. The extracts were compared, and any differences were checked and resolved through discussion. The following information was extracted: full study references (author names, country, article title, year of publication, type of article, and journal), methodology (study area, type of natural resources evaluated, sample size and characteristics, type and nature of evaluation, evaluation methodology, models, parameters, and basic assumptions, if applicable), and results (monetary and other values).

The two reviewers used appropriate tools to assess independently the risk of bias in the studies. Disagreements were discussed by both reviewers and resolved by a third when necessary.

2.6. Risk of bias in individual studies

The risk of bias in individual studies was assessed and discussed in the results section (in particular in 3.3. Risk of bias within studies).

2.7. Synthesis of results

We used the Colandr database to include or exclude studies according to the eligibility criteria. Results of the included articles that were not suitable for a meta-analysis (i.e., qualitative results) are summarized in a table created for this purpose for each study. Information was extracted from each study to describe the economic valuation of forest degradation.

2.8. Risk of bias in the overall studies

We assessed the different risks of bias, namely publication bias (omission of studies), selection report bias (omission of results), omission of summary data, and omission of participants using the Cochrane risk of bias assessment tool [37].

3. Results

3.1. Studies selected

A total of 10,095 articles were identified from the database search (**Figure 1**). After rejecting 1251 duplicate articles, the titles and abstracts of the remaining 8844 articles were examined by the two reviewers for their relevance to the economic valuation of forest degradation. It was found that 44 articles were deemed eligible. The full text of these 44 articles was examined with a fine-tooth comb, and 32 articles were rejected because of the evaluation method (non-economic evaluation), five articles were excluded because of a non-compliant evaluation object, and two articles were rejected because of the evaluated natural resource was not a forest. Finally, five articles including a systematic review were included in the study: one article published in 2016, one in 2017, one in 2019, and two in 2021.

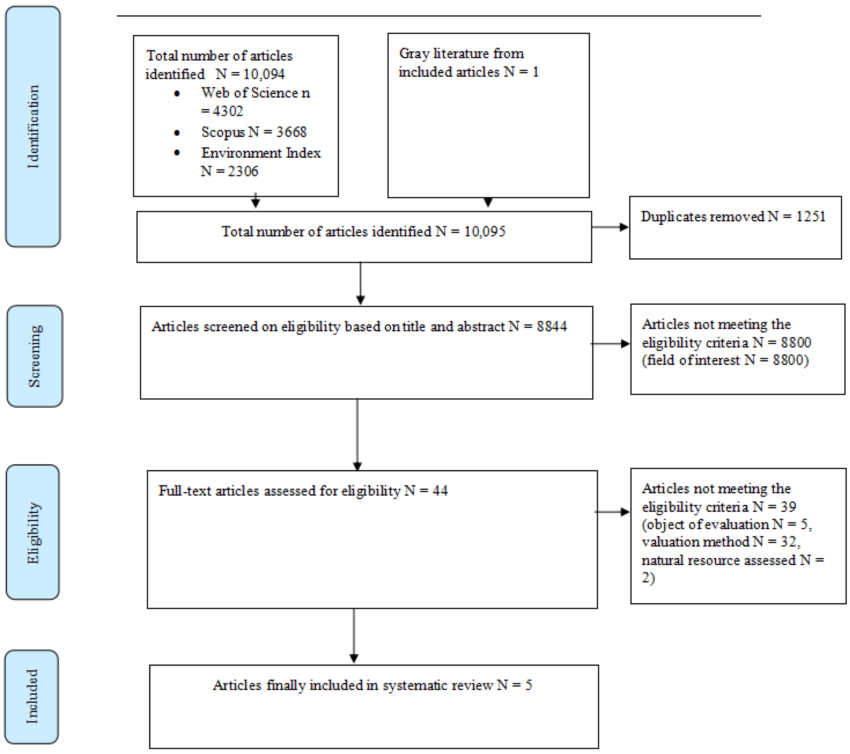

Figure 1. Flow chart of the literature search and selection process for a systematic review of the economic valuation of forest degradation.

3.2. Characteristics of the studies

At the end of the process, the five studies selected were [30,38–41]. The characteristics of these studies are summarized in **Tables 2** and **3** through the extraction of their data.

Table 2. Data extraction from selected articles.

Study						Population				Intervention and comparison	
Study title	**Document type**	**First author**	**Year pub**	**Journal**	**Country**	**Study area**	**Natural resources assessed**	**Sample characteristics**	**Sample size**	**Valuation type**	**Nature of evaluation**
Integration of different environmental valuation methods to estimate forest degradation in arid and semi-arid regions	Article	Mohammad Majdalawi	2016	International Journal of Sustainable Development & World Ecology	Jordan	Northern Jordan: Ajloun and Debeen	Forest	Arid and semi-arid zone	53% of Jordan's forest cover	Prospective: 2014 baseline year; 2,044 (30 years) and 2,114 (100 years) assessments	Erosion assessment Evaluation of the value of lost recreation areas Assessment of income from lost timber Assessment of expected loss of forest area (ha) Assessment of expected loss/damage of forests (reforestation)
Valuation of terrestrial and marine biodiversity losses caused by forest wildfire	Article	Roi Durán-Medraño	2017	Journal of Behavioral and Experimental Economics	Spain	University of Vigo	Terrestrial and marine biodiversity	Social science students (Economics, Finance, Tourism, Human Resources Management) with 33% male and 67% female. No natural science students were included. 66% of the sample came from urban areas and the rest from rural areas. More than 50% practiced recreational activities in the areas, and 15% did recreation in the forest areas	240 individuals	Retrospective assessment	Assessment through externalities related to forest fires (loss of forest biomass, increase in forest pests and diseases, loss and displacement of local wildlife, soil erosion, and loss of marine biodiversity)
Incorporating environmental costs of ecosystem service loss in political decision making: A synthesis of monetary values for Germany. NB: We retained the part relating to the loss of tropical forest	Review	Johannes Förster	2019	PLoS ONE	Germany	11 Databases: Externalities Data Review; Environmental Valuation Database; Marine Ecosystem Service Database Environmental Valuation Database; Marine Ecosystem Service Marine Ecosystems; Partnership for Environment and Recreation (non-market); Partnership for Environment and Recreation and Recreation (non-market) Values-Valuation Studies; National Ocean Economics Program; Ecosystem Service Valuation Database; Web of Science; Datenbank "Dokumentation Natur und Landschaft- online"; Karlsruhe Virtueller Katalog; Ojea et al. [1].	Forests and wetlands	109 monetary valuation studies of regulatory and cultural ecosystem services (ES)	6 of 109 selected articles fulfilled the quality criteria	Retrospective assessment	Loss of ESs due to conversion of tropical rainforest to grassland or arable land

Table 2. (*Continued*).

Study						**Population**				**Intervention and comparison**	
Study title	**Document type**	**First author**	**Year pub**	**Journal**	**Country**	**Study area**	**Natural resources assessed**	**Sample characteristics**	**Sample size**	**Valuation type**	**Nature of evaluation**
Forest fires and losses caused by fires—an economic approach	Article	Beata Sadowska	2021	WSEAS Transactions on Environment and Development	Selected European countries, including Poland	Forest fires in selected European countries, including Poland	Forest	All forest fires in selected European countries, including Poland	All wildfire statistics published between 2014 and 2018 and state forest financial and economic reports for the same period	Retrospective assessment	Assessment of the area and value of forests lost to fire in selected European countries, including Poland
Economic losses from natural disturbances in Norway spruce forests—a quantification using Monte-Carlo simulations	Article	Thomas Knoke	2021	Ecological Economics	Norway	Spruce forests	Forest	Land with associated spruce stands with different rotation periods	1 ha of spruce plantation	Prospective assessment for 1,000 years	Assessment of economic losses related to climate change through natural disturbances. The sensitivity of economic losses was obtained by assessing changes in expected land value in consideration of standing timber volume and worst-case values for economic return

Table 3. Data extraction from selected articles (continued).

Intervention and comparaison					**Outcome**
Study	**Nature of valuation**	**Valuation method**	**Model**	**Settings (parameters)**	
Majdalawi et al. 2016	Erosion assessment (1)	Productivity method: This method is used to provide an alternative estimate of damages such as yields that are affected. It is used to estimate the economic value of ecosystem products or services that contribute to production. It is based on a comparison of yields before and after a crisis to show that they have declined over time. Thus, changes in the quantity or quality of a resource will lead to changes in the production and/or productivity of other inputs and may affect the price and/or quantity supplied of the final good [42].		Baseline year 2014 Cost of soil erosion (from previous studies) = 30 JD (Jordanian Dinar)/ha	
	Assessment of the value of lost recreation areas (2)	Transportation cost method		Baseline year 2014 Cost of loss of recreation areas (according to World Bank studies in 2004) = 84 JD/ha After taking inflation into account, this amount was 180 JD/ha in 2014	

Table 3. (*Continued*).

Intervention and comparaison					Outcome
Study	**Nature of valuation**	**Valuation method**	**Model**	**Settings (parameters)**	
	Evaluation of the income from the loss of wood (3)	The study area had 5 forest types for which the distribution of tree species and the estimated wood production of each type were known (previous studies)		Baseline year 2014 Number of trees/ha: 250 Amount of wood (in m^3/tree) produced by each type of forest and tree was known Price of wood was known (see market price)	
	(4) = (1) + (2) + (3)				Expected value in 2044 (30 years) in million JD = 379 ($1 = 0.71 DJ) Expected value in 2114 (100 years) in million JD = 31,624
	Estimated loss of forest area (ha) (5)	A growth rate method was used to estimate the future decline of natural forest areas as a degradation rate. The logarithms of the two values were calculated, and the degradation rate was estimated by finding the difference between the two logarithmic values and dividing the difference by 64 years (2014–1950). As a result, the degradation rate was approximately 0.7%. Based on the rate of forest degradation, the area of forest lost was estimated for each year considering the fact that forest once lost is a reduction in value for all subsequent years. Because of this, the total losses of the forest were estimated by the sum of the losses of each year with those of the previous years (by capitalization)		Baseline year 2014 Degradation rate 0.7% (rate obtained by using the logarithm of the two values: area of forest lost between 1950 and 2014 and growth rate	Expected value in 2044 (30 years) = 54,056 ha Expected value in 2114 (100 years) = 509,087 ha
	Assessment of expected loss/damage of forests (reforestation) (6)	The habitat or resource equivalency analysis (HEA or REA): This methodology allows the benefits of the use and non-use of environmental resources to be captured through its principle of providing services for lost services and compensation for natural resource damages [43]. The main concept behind the AEM method is that the public can be compensated for resource losses through replacement or restoration projects that provide additional resources of the same type, in this case by assuming that the forest area will be replaced by a new forest (reforestation) and its value will be considered the value of the compensation.		Baseline year 2014 Annual discount rate 8% Assumption: restoration will take place every following year to immediately recover the degraded area Value of restoration according to previous studies = 6000 JD/ha in 2004 Lost forest area: accounting for inflation this amount is 15,000 JD/ha in 2014	Expected value in 2044 (30 years) in million JD = 217 Expected value in 2114 (100 years) in million JD = 11,422
	(4) + (6) and taking into account (5)				Expected value in 2044 (30 years) in million JD = 596 ($1 = 0.71 JD) Expected value in 2114 (100 years) in million JD = 43,046

Table 3. (*Continued*).

Intervention and comparaison					**Outcome**
Study	**Nature of valuation**	**Valuation method**	**Model**	**Settings (parameters)**	
Durán-Medraño et al. 2017	Assessment through externalities related to forest fires (loss of forest biomass, increase in forest pests and diseases, loss and displacement of local wildlife, soil erosion, and loss of marine biodiversity)	Discrete choice experiment (DCE), which is a stated preference method based on individual preferences. In DCE studies, individuals choose between several hypothetical programs that affect their well-being. The willingness-to-pay method is used as part of the DCE model. Individuals are asked, on the basis of a questionnaire, how many hours they are willing to work to protect the forest as well as their hourly rate.	(1) $U_{njt} = -\alpha_n p_{njt} + \beta'_n x_{njt} + \varepsilon_{njt}$ $Var(\varepsilon_{njt}) = k_n^2(\frac{\pi^2}{6})$ Dividing Equation (1) by the scale parameter k_n, we have (2) $U_{njt} = -\lambda_n p_{njt} + c'_n x_{njt} + \varepsilon_{njt}'$ (3) $U_{njt} = -\lambda_n p_{njt} + (\lambda_n \omega_n)'_n x_{njt} + \varepsilon_{njt}'$	U is the utility that a decision maker *n* derives from choosing alternative *j* in choice set *t* and is a function of cost *p* and a set of non-cost attributes x; α_n and β_n vary randomly over the decision makers, thus incorporating heterogeneity, and the error term, ε_{njt}, is iid. It is assumed that ε_{njt} is a distributed extreme value and the variance of njt of ε can be different for different decision makers $Var(\varepsilon_{njt}) = k_n^2(\frac{\pi^2}{6})$, where k_n is the scalig parameter for *n* decision makers (1) $\lambda_n = (\alpha_n/k_n)$, $c_n = (\beta_n/k_n)$ and ε_{njt}' iid standard at an extreme value with constant variance $\frac{\pi^2}{6}$ (2) Because the WTP for an attribute is the ratio of the attribute coefficient and the price coefficient $\omega_n = (c_n/\lambda_n)$, then the utility function can be rewritten as (3)	The average value in number of working days was 10 days for an average monetary value of €400 per individual ($1 = €0.84 in 2017)
Förster et al. 2019	Loss of ecosystem services due to conversion of tropical rainforest into grassland or arable land	Criteria have been identified to assess the adequacy of valuation studies to derive cost estimates for loss of ecosystem services (ES): a. The focus of the valuation study was on the loss of ESs associated with the conversion of tropical rainforest into grassland or arable land; b. There was an explicit description of the biophysical and socio-economic context; c. Transparent study design, methods, and underlying assumptions; d. Monetary values referred to a distinct and clearly identifiable ES or set of ESs; e. Monetary values were derived using common valuation methods (cost-based or benefit-based approaches); f. Monetary values were expressed in €/ha or allowed for currency conversion and unit adjustment; g. Representativeness of monetary values: the reasoning for the minimum–maximum ranges of values was explained by a minimum–maximum range in biophysical or socio-economic factors (e.g., ecosystem carbon content/ha). Monetary values were adjusted for inflation to 2014 values using the Consumer Price Index. Values were adjusted to Purchasing Power Parity. Values were converted to groups of similar units (€/ha/year; €/ha; €/person/year; other)	$Value\ in\ €_{2014} = Value_{deferred} * \frac{CPI_{2014}}{CPI_{Valuation\ year}}$ $Value\ in\ €_{2014} = Value_{2014} * \frac{PPP_{Germany}}{PPP_{Valuation\ year}}$	CPI: Consumer Price Index PPP: Purchasing Power Parity	Most monetary values come from valuation studies that apply a combination of valuation methods. The use of replacement costs as a means of valuing ESs is a common approach in Germany, followed by choice experiments. In tropical regions, willingness-to-pay and market price methods dominate. The database contained 171 monetary values for tropical forest ESs from a total of 23 monetary valuation studies. Of the 171 monetary values, 114 met the criteria for transparency of study design and methods. Five aggregate monetary values met the previous criteria with more relevance to the possible costs involved in the loss or degradation of ESs

Table 3. (*Continued*).

Intervention and comparaison					**Outcome**
Study	**Nature of valuation**	**Valuation method**	**Model**	**Settings (parameters)**	
Sadowska et al. 2021	Assessment of the area and value of forests lost to fire in Europe including Poland	Critical analysis of the literature on the subject Literature search method Comparative method Method of induction and synthesis Techniques of graphic presentation of data	LFV= (IEV − IV) × L × A × P or LFV = VCI × L × A × P	LFV: Lost forest value in Polish currency; IEV: Index of expected value of 1 ha of standing timber at the age of the tank well; IV: Index of the value of a hectare of standing timber at the age of early felling of this stand; CVI: Value of costs incurred to establish and maintain 1 ha of stand; L: Stand stocking level, which is the quotient of the actual stand volume of trees at the early felling age and the potentially achievable stand volume; A: Area of the stand burned (ha) P: Current official selling price of 1 m^3 of wood in Poland	The economic value of fire losses in Poland varied over the years analyzed, with the highest values in 2015 (6.6 million Zloty), and the lowest in 2017 (1.3 million Zloty). 2018 saw an upward trend with 4.8 million Zloty. ($1 = 3.93 Zloty)
Knoke et al. 2021	Assessment of economic losses related to climate change through natural disturbances. The sensitivity of economic losses was obtained by assessing changes in expected land value in consideration of standing timber volume and worst-case values for economic return	Monte-Carlo simulation method (MCSM). MSMC is a common method to quantify uncertainties based on random experiments in order to estimate the possible ranges and distributions of, for example, future ecological or financial data. To calculate the expected land values, a finite, but very long-time horizon (1000 years) was defined. Over this period, damages caused by natural disturbances as well as stochastic events were simulated. To obtain the economic returns of the Norway spruce, a simulation of the net revenue streams over the 1000 years for each of 20,000 Monte-Carlo iterations. Then, these revenues were discounted and their sum calculated per iteration. To approximate the expected value for the economic criteria, the arithmetic mean of all 20,000 iterations was used. Sets of these simulations (each with 20,000 iterations) for a range of possible rotation periods, T = 30, 40, 50, 60, 70, 80, 90, 100, and 110 years, respectively, were used to find the optimal rotation period. The optimal rotation was identified as the one that maximized the average land expectancy over all iterations. The maximum value of the land expectancy was used to derive the possible economic losses due to disturbance	$R_i = \sum_{t=a}^{T+a} n_{ti}.b^t with b = (1+d)^{-1}, \forall p \in P, c \in C$ $R = E(R) \backsimeq \frac{1}{n}\sum_{i=i}^{n} R_i$ If a = 0, then R = ELV If a > 0, then R = FV	Ri: Economic return in €/ha for the iteration i; t: Time in years; a: Age of the forest in years; if a = 0, we have the expected land value (ELV) for bare land without standing timber; if a > 0, we have the forest value (FV); T: Period of consideration in years (T = 1000 in this study); n_t: Net income flow in €/ha at time t; b^t: Discount factor or coefficient; p: Period of rotation considered; P: Set of rotation periods; c: Age class considered; C: Set of age classes; E(.): Expected value; n: Number of Monte-Carlo simulations (n = 20,000 in this study); i: Index of individual Monte-Carlo simulations (iterations); d: Discount factor (d = 0.015 in this study); ELV: Expected land value; FV: forest value, the sum of ELV and standing timber value	Economic losses induced by disturbances varied considerably, depending on the valuation approach applied: -€2611 to −€34,416 (in 2021; $1 = €0.88). After accounting for extreme events and the impact of disturbances on standing timber, losses were 262 to 1218% higher than the damages derived from standard valuation approaches that neglect these aspects

3.3. Risk of bias within studies

To reduce bias, two reviewers set up and used appropriate tools such as Colandr and Zotero to examine independently the risk of bias in the studies. Disagreements were discussed by both reviewers and addressed by a third when necessary.

3.4. Risk of bias in the overall studies

To reduce the overall publication risk, the studies searched in the databases were restricted to articles, journals, conference reports, or conference proceedings. We are aware that beyond this provision, entire studies may be missing from our analysis if they were never published, published in obscure locations, or inappropriately indexed in the databases. For the remaining biases, the risk of bias was assessed using the Cochrane Risk of Bias Assessment Tool [37]. The assessment of the different biases is summarized in **Figures 2** and **3**.

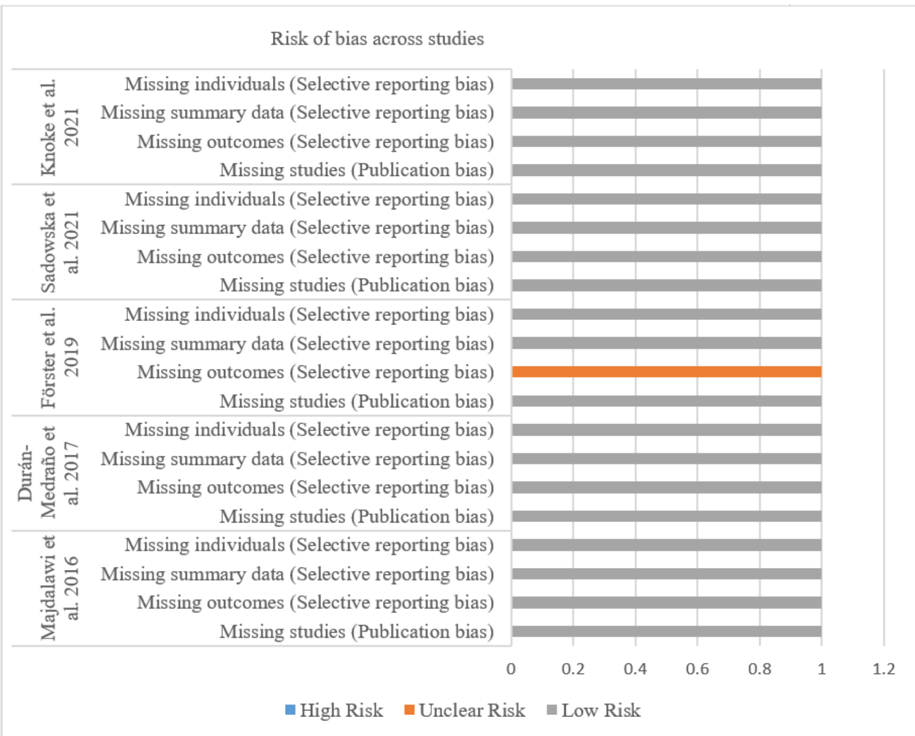

Figure 2. Risk of bias assessment of studies included in the systematic review using the Cochrane tool.

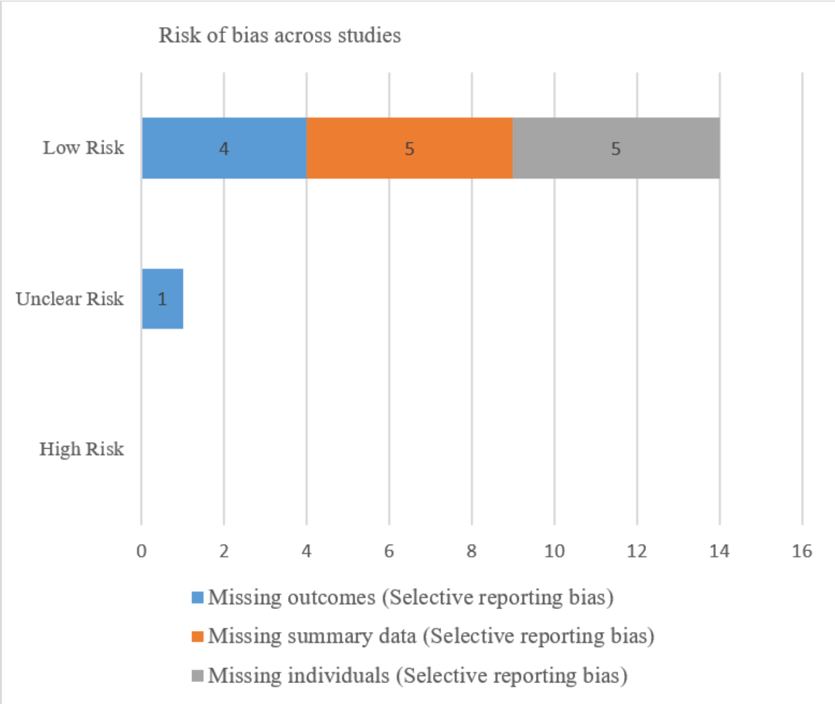

Figure 3. Summary of the level of risk of bias for studies included in the systematic review on the economic valuation of forest degradation. Risk of bias was assessed using the Cochrane risk of bias assessment tool.

3.5. Synthesis of studies

From the different results, it was found that:

Majdalawi et al. 2016: The assessment was done using the productivity method, transportation cost method, market price method, degradation rates, and habitat equivalence analysis method to assess, respectively, land yields (erosion assessment), value of lost recreation areas, timber losses, forest area losses, and reforestation. The sum of these values gave an estimate of forest degradation for 30 years and 100 years from 2014. Thus, degradation was estimated as 596 million Jordanian Dinars ($1 = 0.71 JD) in 2044 and 43,046 million JD in 2114.

Durán-Medraño et al. 2017: The evaluation used the contingent valuation method and a discrete choice experiment (stated preferences) for each individual based on the externalities of forest loss (here, forest loss, increase in pests and diseases, loss of wildlife, erosion) to express the amount of time they are willing to work to protect the forest and their hourly rate, thus the willingness to pay to protect the forest. An average value was determined (10 days/person for a value of €400). $1 = €0.84 in 2017.

Förster et al. 2019: This study, which was a systematic review, assessed, among other things, the conversion of rainforest to grassland or arable land and thus the loss of forest. Most studies apply a combination of valuation methods. The use of replacement costs as a means of valuing ESs is a common approach, followed by choice experiments. In tropical regions, willingness-to-pay and market price methods are given priority. To compare values, the study used the Consumer Price Index and Purchasing Power Parity with 2014 as the baseline year. However, the study did not give a summary mean or median value.

Sadowska et al. 2021: Based on data from previous studies and official national statistics of the country concerned, this study determined the following quantities: the value of forest lost to fire through an index of the value of costs incurred to establish and maintain 1 ha of stand, the stocking level of stands (i.e., the quotient of the actual volume of stands of trees at the first age of felling and the volume potentially achievable by this stand), the area of the burned stand, and the current official selling price of 1 m^3 of wood (for the country concerned). Economic values were calculated for several years. The highest value was recorded in 2015 (6.6 million Zloty), and the lowest in 2017 (1.3 million Zloty). 2018 saw an upward trend with 4.8 million Zloty ($1 = 3.93 Zloty).

Knoke et al. 2021: This was an assessment of economic losses related to climate change through natural disturbances. The sensitivity of economic losses was obtained by assessing changes in expected land value in consideration of the standing timber volume and worst-case values for economic return. The Monte-Carlo simulation method (MCSM) was used. MSMC is a common method for quantifying uncertainties based on randomized experiments to estimate ranges and possible distributions of, for example, future ecological or financial data. To calculate the expected land values, a finite but very long-time horizon (1000 years) was defined. Over this period, damages caused by natural disturbances as well as stochastic events were simulated. To obtain the economic returns, a simulation of the net revenue streams over the 1000 years for each of 20,000 Monte-Carlo iterations was performed. Then, these revenues were discounted and their sum calculated per iteration. To approximate the expected value for the economic criteria, the arithmetic mean of all 20,000 iterations was used. Sets of these simulations (each with 20,000 iterations) for a range of possible rotation periods, T = 30, 40, 50, 60, 70, 80, 90, 100, and 110 years, respectively, were used to find the optimal rotation period. The optimal rotation was identified as the one that maximized the average land expectancy over all iterations. The maximum value of the land expectancy was used to derive the possible economic losses due to disturbances. The economic losses induced by disturbances varied considerably, depending on the valuation approach applied: between −€2,611 and −€34,416 (in 2021; $1 = €0.88). After accounting for extreme events and the impact of disturbances on standing timber, losses were 262 to 1218% higher than the damages derived from standard valuation approaches that neglect these aspects.

3.6. Analysis of the strengths and weaknesses of each study's methodology

An analysis of the strengths and weaknesses of the methodology of each study is summarized in **Table 4**.

Table 4. Analysis of the strengths and weaknesses of the methodology of each included study.

Study	Strengths	Weaknesses
Integration of different environmental valuation methods to estimate forest degradation in arid and semi-arid regions (Majdalawi et al. 2016)	1) Each ecosystem service (ES) loss was valued (fertility loss by the productivity method, timber loss by the market price of timber, recreation loss by the transportation price method); 2) Reforestation was estimated by its cost at the baseline period by taking into account the rate of degradation and the discount rate	1) Of all the methods used, none of them made an economic assessment of NTFPs that have significant value; 2) It cannot be assumed that the rate of degradation was constant from year to year; 3) The values found were only an update of values from previous studies taking into account the inflation rate; 4) All the services lost through ecosystem degradation were not evaluated by the methodologies used (water protection, carbon sequestration, loss of wildlife, etc.). In total, the methods used did not allow for the evaluation of environmental losses
Valuation of terrestrial and marine biodiversity losses caused by forest wildfire (Durán-Medraño et al. 2017)	Discrete choice experiment was a stated preference method based on individual preferences	The main weakness was in the quality of the individuals in the sample: students of social sciences who for the most part (66%) were from urban areas. Indeed, the discrete choice experiment made it possible to evaluate the economic value of the environment by estimating, in monetary terms, the gain or loss of well-being of an individual, through his or her declarations, due to an improvement or degradation of the quality and/or quantity of goods and services produced by a natural asset [44]. An individual who is best placed to appreciate a gain or loss of well-being of a natural asset is someone familiar with the asset concerned. Therefore, the amount he is willing to pay is done so with full knowledge of the facts
Incorporating environmental costs of ecosystem service loss in political decision making: a synthesis of monetary values for Germany (Förster et al. 2019) NB: We retained the part relating to the loss of tropical forest	1) Systematic review; 2) Using willingness-to-pay and market price methods to value tropical forest ES; 3) For tropical forests, frequently valued ES included “biodiversity (habitat, species)”, “food supply, multiple ES bundles”, “material supply” and “physical experience (recreation)”. The study provided a minimum range of monetary values (adjusted for inflation and with 2014 as the baseline year) for each service	No mean or median value of overall synthesis for all services
Forest fires and losses caused by fires—an economic approach (Sadowska et al. 2021)	1) Leveraging wildfire statistics published between 2014 and 2018 and the state of the country’s forests financial and economic reports; 2) Induction and synthesis method	The monetary valuation focused only on the value of the loss of wood: the other lost functions of the forest were not valued
Economic losses from natural disturbances in Norway spruce forests—a quantification using Monte-Carlo simulations (Knoke et al. 2021)	1) Monte-Carlo simulation method is a common method for quantifying uncertainties based on random experiments to estimate ranges and possible distributions of, for example, future ecological or financial data; 2) Determination of the present value of the forest (value of land + value of timber) on a long-term basis that takes into account disturbances (uncertainties)	This method determined only the value of the land and the wood. The value of a forest is not limited to that

4. Discussion

We included a total of five articles that evaluated the actual economic cost of forest loss. Of these, only one was a systematic review. This result is sufficient evidence of the difficulty of finding systematic reviews in the field of biodiversity conservation as opposed to health science [35,36].

The current study showed that forest degradation assessments were conducted in an indirect manner. The articles assessed the services provided by the forest, including soil fertility, recreation areas, wood supply, wildlife habitat, and carbon sequestration. However, the assessment omitted soil erosion and water quality [1,40]. Similarly, many studies valued the forest as its direct use value (wood and non-timber forest products, recreation and science/education services, etc.), its indirect use value (water and soils, carbon sequestration, etc.), and/or its option value (the possibility of using the forest in the future) [41–43].

Therefore, we conclude that there are many ways to assess the loss of forest resources. This is one of the difficulties of the economic valuation of forests: the choice among methods and the synthesis of their results [45]. We have identified the market price method, the transportation cost method, the mixed methods, the replacement cost method, the habitat equivalence analysis method, and to a lesser extent the mathematical methods and the stated preference method. The market, when it exists, is used to assess the value of a natural asset [47]. The market price method is often more widely used [2], but some natural resources do not have a market value. Non-market valuation methods are then used [48], among them the transport cost method [40,41,44] and the replacement cost method [30,40]. The habitat equivalence analysis method is also used for natural resource valuation [43]. Finally, the stated preference method has been used in recent years to assess the non-market value of natural resources [2,40,43,45–48].

All of this prior work justifies the use of the identified methods to assess forest degradation. Economic valuation aims to meet the monetary expectations of the public to achieve environmental preservation goals [53], and decision making is increasingly based on economic considerations, including cost-benefit analysis [54]. The key factor in achieving desired economic outcomes and the likelihood of sustainable economic benefits for a project is economic analysis [52]. Estimates of the economic costs and benefits of land use options can inform decision making about the multiple benefits that biodiversity and ecosystems provide to human well-being as well as about the economic consequences of ecosystem loss [50,51]. For example, the economic benefits of biodiversity and ecosystem conservation have been shown to exceed the costs of conservation when multiple benefits of ESs are considered [56]. ES valuation is an approach to support decision making that involves the environment (trade-offs between production and environmental conservation) [51].

In summary, in the economic evaluation of forest loss, several parameters are important. First, the valuation must cover all the services lost: direct and indirect values as well as the option value [41–43]. Second, although no single methodology is used to evaluate forest ESs in general [45], the willingness-to-pay method is particularly useful for evaluating the ESs of tropical forests [30]. However, when the willingness-to-pay method is used, it is appropriate to choose individuals who can better appreciate the welfare gain or loss of the natural asset. Indeed, the discrete choice experiment makes it possible to assess the economic value of the environment by estimating, in monetary terms, the gain or loss of well-being of an individual, through his or her statements, due to an improvement or degradation in the quality and/or quantity of goods and services produced from a natural asset [44].

One obvious observation from the included studies is that they made no mention of institutional weakness. Indeed, we note this weakness from the point of view of proactivity and the implementation of existing regulatory frameworks (treaties and laws). Although it is true that there are few ES indicators available to governments [30], the implementation of existing indicators is a problem. For example, Pata et al. [57] point to the need to use renewable energy research and development to improve environmental quality and reduce the ecological footprint. Although the race for alternatives to fossil fuels is very much on, investment in renewable energy research is also lacking. Furthermore, forests are invaded by uncontrolled logging and pierced by road infrastructures.

This study makes a call to stakeholders for the optimal and sustainable governance of forest resources. We wish to name policymakers, nature conservation organizations, experts, researchers, and the direct users of our forests.

5. Conclusion

The aim of this study was to identify the methods that previous studies used to assess forest degradation in economic terms. These studies showed that the economic evaluation of forest degradation was indirect in character and focused on the various ESs that the forest provided (supply services, regulatory and support services, cultural services). The various evaluation methods can be grouped into two categories: market (timber loss) and non-market (individual preferences). It is advisable to use the willingness-to-pay method and the market price method to evaluate tropical forests ESs. However, some methods, despite receiving growing interest in recent years, notably the stated preference method, were less used. These estimates, although economic, are an important challenge to governments and stakeholders for participatory, social, and sustainable governance of forest resources.

This research appears to be one of the few systematic reviews to study the economic valuation of forest degradation. Future studies could either be a little more flexible in their eligibility criteria or identify articles from a longer period than ours.

6. Limitations

The main limitation of this analysis was that it identified and included a very small number of studies. This may have limited the analysis of the data. For example, it was not possible to quantitatively pool the results of the studies. To avoid this limitation, future studies could either be a little more flexible in their eligibility criteria or identify articles from a longer period than ours.

However, this review had some strengths. The third referee of this study was not only an expert in forest economics but also a teacher-researcher in the same field. This gave more credibility, improved our results, and eliminated any potential bias. In addition, we used a rigorous methodology to conduct the different steps of the analysis; thus, our results are both complete and reproducible. The relevance of our results favors their use by governments, forest conservation organizations, researchers, and students

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Review

Long and short term implications of mineral mining operations in Sierra Leone: A review

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Abstract: Sierra Leone is among the few countries endowed with substantial mineral resources deposits in Africa. This review throws light on the long- and short-term positive impact of the mining sector in Sierra Leone. Over the past decade, the revenue derived from mineral mining has had little impact on the economic development of the country. According to history, extensive mineral mining operations is traced back to the early 1930s. Nonetheless, the inception of mineral extractions in Sierra Leone has been characterized by political instability, war, biodiversity loss, corruption, hardship among others. Based on available literature, mineral extraction in Sierra Leone has directly or indirectly impacted the 1), environment (ecosystem and biodiversity) 2), governance and leadership (stakeholder's consultation) and 3) economic growth and development. The common negative impact are environmental pollution, degradation and social issues such as sexual violence, teenage pregnancy, early marriage, prostitutions, school dropout and spread of transmissible diseases among other issues. The source of data for this review was acquired from the secondary source. Information was source from both published and unpublished materials of interest. Key words such as mineral mining, mineral resources, mining benefits, mining policies, mining challenges were searched for important information on the subject matter. In some mining edge communities across Sierra Leone, protest and other human right abuses perpetrated by company's authorities and security officials is common within these communities in Sierra Leone. On the other hand, mineral mining has served as a means of sustainable livelihood booster for deprived mining edge communities in Sierra Leone. Additionally, some mining edge communities in Serra Leone enjoy better economic conditions from the cooperate social responsibility (CSR) scheme of most mining companies. Alternately, mineral mining has also been a source of political tension and tradeoff between local resident and mining companies/governments. To remedy this situation, the government in recent years, has enacted many policies, legislations and regulations that supports the judicious extraction and management of minerals for the benefits of all in Sierra Leone. It is therefore recommended that, best international practices and standard operating procedures related to mining extraction be adopted and applied across all mining sites in Sierra Leone. This will help in mitigating the human right abuses trade-off between mining communities and mining companies for a better future.

Keywords: Sierra Leone; mining; mineral; developing countries; communities; resources; operation

1. Introduction

Sierra Leone is among the least developed nations endowed with abundant mineral resources. On the global stage, Sierra Leone is ranked 10th among the world's diamond and rutile producers based on volume [1]. Extensive mining of minerals in Sierra Leone could be traced back to 1930 and has since been in the spotlight for both economic and social unrest [2]. The mined minerals range from; Iron Ore, Diamonds, Gold, Bauxite, Rutile, Alumina, Petroleum, Titanium and Zirconium among others [3]. When sustainably mined, these minerals thus have multiple socio-economic importance on the living standard at the national, regional and local level. Equally, theses minerals could serve as the engine of economic and sustainable development of Sierra Leone. Over the years, revenue from mineral extraction has been Sierra Leone's second largest economy booster after agriculture and the main source of export, employment and rural livelihood facilitator. Large scale and artisanal mining operations have over the past decades provided jobs for both skilled and unskilled labor across the country. Five types of mineral licenses right are given in Sierra Leone namely; large scale 1) exploration, 2) small scale 3) artisanal 4) and 5) reconnaissance [4]. Mineral mining incentives in the form of license fee, taxes, surface rent and custom taxes among others has provided huge revenue for successive governments to undertake pressing infrastructural and social services projects across the country [5]. For instance, in 2012, Sierra Leone gross domestic product (GDP) grew to 15.2% as a result of the boom in iron ore production. That same year, 71% of the total export income was from mineral proceedings [1]. Illegal mining has equally provided thousands of employment for jobless youths in mineral rich communities in Sierra Leone. The overdependence on the mining sector in Sierra Leone is linked to the high GDP contribution potential and export earning of the sector since 1930. In remote areas where minerals are located, mining activities have provided a sustainable source of livelihood for thousands of households [6].

Basically, mineral mining investment is capital intensive with high risk and uncertainty but at the same time it's a highly rewarding investment [7]. Nonetheless, critics argued that, absence of satisfactory infrastructure designed to support sustainable mining operations has the tendencies to prevent direct future foreign investment in the mining sector [8]. Secondly, the civil war that lasted for 11 years reversed all previous gains made by governments to strengthen the mineral sector in Sierra Leone. Additionally, weak mineral extraction supervisory institutions and corruption has been deterring the actual realization of the full benefits of mineral extraction in Sierra Leone. Sierra Leone is under huge environmental pressure and was recently ranked 177 out of 180 countries for the 2020 Environmental Performance Index (EPI) [7] with mineral mining being the main culprit. Furthermore, research has proven that, mineral mining is the second major threats against biodiversity boom after agriculture in Sierra Leone [9]. In Sierra Leone, most mining companies seize operations abruptly hence stimulating huge economic, social and environmental implications for the mining communities after closures.

Sierra Leone is among the least developed nations endowed with abundant mineral resources. However, opinions are divided on the role play by mining operations revenue since the inception of mining activities in Sierra Leone. This review examines both the positive and negative effects of mining activities in Sierra Leone. The review further highlights the various reforms undertaken by the government of Sierra Leone to improve the mining environment over the past years. The article is poised to answer the following research questions 1) what are the various policy reforms undertaken by the government over the past year 2), How has the revenue generated from extracted mineral resource contributed to the economic development of Sierra Leone 3) what are the social and environmental challenges emanating from mineral mining in Sierra Leone 4) and what is the livelihood implication of mineral mining especially to mining edge communities. With these research questions, this review article is poised to close the knowledge gap on the status of mineral mining and its development implication in Sierra Leone. Therefore, analyzing the long and short term positive and negative impacts of mineral mining in a developing country like Sierra Leone has the potential to inform relevant stakeholders and other key policy makers on the consequences of mineral mining across Sierra Leone. Results from this review will inform policy makers and provide useful insight on the long and short term impact of mineral mining in Sierra Leone. In summary, the main focus of this review is to highlights the long and short term implication of mineral mining on the environment in Sierra Leone.

2. Review of relevant literature on mineral mining implications in Sierra Leone

Mining in Sierra Leone is considered a great source of income for both citizens and foreign investors. The sector provides income continuously, employs all class of citizens, promote income distribution, community infrastructure improvement among others. Sierra Leone’s mining sector has over the years been considered a key driver to the sustainable development of the country with great investment opportunities. The country is endowed with minerals of great global interest like diamonds, iron ore, rutile, gold among others [10]. However, the sector has over the years been characterized by both negative and positive implications such as death, unrest, income to household, source of revenue to government, disrupt societal and family norms of mining communities among others. Furthermore, mining has reduce ecosystem functions and results in biodiversity and habitat loss over the years [11]. Mineral mining negative implication is on the increase due to the fact that the price and value of minerals has doubled and as a result fast income is realized in the mining sector as compared to agriculture and other alternative sources of livelihood. In Sierra Leone and other part of Africa, mining on the artisanal scale is considered a quick path out of abject poverty or slow source of income in communities were other social income driven jobs are unavailable [12]. The quest to revolutionized the mining sector over the years have resulted to the establishment of agencies like the “Extractive Industries Transparency Initiative”, “Global Reporting Initiative”, “International Cyanide Management Code”, “International Council on Mining and Metals” among others [13]. These bodies are charged with the responsibility to bring degradation and biodiversity loss sanity into the mining sector [14]. Mining activities have destroyed high conservation areas and biodiversity hotspot across Sierra Leone. In addition, ecosystem services and functions are being threatened by mining activities in rural areas. Furthermore, mining emit carbon directly through the use of heavy machines to process the minerals thereby impacting the environment negatively [15].

Mining instruments in Sierra Leone

Over the years, a plethora of mining policies, legislations and regulations have been enacted to aid the judicious extraction and management of minerals for the benefits of all in Sierra Leone. These policies are geared towards the improvement of mineral mining integrity for the maximization of benefits associated with mining. They include, the Mines and Mineral Act, 2009, the National Mineral Agency, 2012, the Environmental Protection Agency 2008, the Extractive Industries Revenue Act of 2018, the Sierra Leone Minerals Policy 2018, the Artisanal Mining Policy 2018 and the Sierra Leone Geodata Policy 2019 (**Table 1**). In order to maximize revenue gained from mineral mining, the government of Sierra Leone has introduced series of reforms aim at rebranding the sector for the sustainable development of the country over the past decades. These reforms are in the form of institutional reforms, established mining policies, mineral agreement criteria, environmental protection improvement measures, mining community financing, environment impact assessment and licenses among others [16,17]. The reforms were designed to overcome governance overlap, corruption and, policy implementation inconsistencies as well as legislative loopholes in the mining sector. The various reforms were further undertaken to improve environmental protection, biodiversity conservation and ecosystem services and enhance mining community financing. This was achieved by reviewing various regulations, policies, Acts, and other legal instruments to enhance a sustainable extraction and exploration of minerals that will be the nation. These policy and institutional reforms are intended to attract more private sector investors within the mining sector. Other benefits expected to be derived from these reforms are the sustainable exploitation of minerals and the possible integration of the division into the national economy and enhance a win-win scenario for the country and investors. It is expected that these policies will strengthened the compliance and monitoring mechanism of mining companies and enhance accountability and transparency within the mining industry [18]. Nonetheless, the Sierra Leone mineral policy is still the legal and legitimate mining policy governing mining activities in Sierra Leone [16,17].

Table 1. Policies and other legislative Instruments governing the mining sector in Sierra Leone.

Policy title	Date of enactment	Status
Constitution of Sierra Leone 1991	1991	NA
The National Minerals Agency in 2012	2012	Agency
The Minerals Act 1927	1927	Amended
Revised Minerals Act in 1960	1960	Amended
The Environment Protection Agency in 2008	2008	Amended
The Mines and Minerals Operational Regulations 2013	2013	NA
The Mines and Minerals Act of 2009	2009	Amended
The Public Financial Management Act of 2016	2016	CA
Mines and Minerals Regulations 2009	2009	Amended
The Extractive Industries Revenue Act of 2018	2018	CA

Table 1. (*Continued*).

Policy title	Date of enactment	Status
Environmental and Social Regulations for the Minerals Sector 2012	2012	CA
The Sierra Leone Minerals Policy	2019	CA
The Artisanal Mining Policy	2018	CA
The Geodata Management Policy	2018	CA
Diamond Cutting and Polishing Act, 2007	2007	NA
Environment Protection (Mines and Minerals) Regulations 2012	2012	NA
The Medium-Term National Development Plan 2019–2023 (MTNDP)	2019	Ongoing
National Land Policy and Land Commission Act 2004	2004	Amended
The National Land Commission Act, 2021	2021	CA
The National Protected Area Authority and Conservation Trust Fund Act, 2012	2012	NA
Mines and Minerals Regulations in 1994	1994	Amended
Mines and Minerals Decree Act	1994	Amended
The National Environmental Policy	1994	Amended
National Environmental Action Plan	1995	Amended
Mines and Minerals (Fees) Regulations in 2008	2008	Amended

Note*** NA = Not amended; CA = Currently applicable.

3. Materials and method

Sierra Leone is a relatively small and low-income country located in West Africa, with a population of about 7.8 million people [19]. Sierra Leone is bordered with Guinea in the north and Liberia in the East. The country is part of the Guinean Congo Basin biome and has a land area of 72,300 sq [20]. The country is rich in terms of minerals such as Gold, Diamonds, Rutile, Iron ore, Chrome, ilmenite, Bauxite among others. In such, the socio-economic development of Sierra Leone depends largely on mineral mining and their associated revenue. Sierra Leone is characterised by high youth unemployment, illiteracy, inequality and precarity, poverty and corruption and was ranked 179 of 188 countries in 2018 by the Human Development Index rating [21].

Data collection method

The data for this review was acquired from secondary sources. Key words like mining, mineral, corporate social responsibility, mineral resources, mining benefits, mining policies, mining challenges were searched for important information on the subject matter. Information was source from both published and unpublished materials of interest [22]. Documents of interest for the review were; published journal articles, governments report, Acts, and policies on mining activities and revenue, workshop and conference proceedings, international partners working on mineral resources sustainability reports and unpublished documents and thesis. In addition, mining company's websites were search to see the corporate social responsibility activities undertaken by various mining companies in the country.

Collected information was analyzed and sorted to extract critical information needed to develop various sections of the article as per [23].

4. Review findings: Mining and economic development of Sierra Leone

Mineral mining plays a critical role in the economic development of developing countries and is considered an important factor for the sustainable and social development of these countries [24] Sierra Leone is categorized as a resource rich nation endowed with massive deposit of diamonds, rutile, bauxite, iron ore, gold among others. Sierra Leone is classified as a resource dependent country with the mining sector contributing a lion share of the country's revenue, export and Gross Domestic Product annually [25, 26]. From time immemorial, revenue generated from mineral proceeds account for the main source of export, foreign exchange revenue and Gross Domestic Products of Sierra Leone. Mineral mining has been the mainstay of the government of Sierra Leone's economy since independence in 1961 [5]. Economic development of Sierra Leone through mining of minerals have been realized through employment opportunities, foreign exchange earnings, foreign direct investment, government revenues and corporate social responsibilities of mining companies. Characterized by higher revenue potential, mineral mining in Sierra Leone has been over the years considered as a sustainable source of wealth use for the development of the country [27]. The mining sector in Sierra Leone contributes significantly to the GDP of the country and account for 50%–65% of export earning year in year out [28,29]. The sources of revenue use for development purpose in the mining sector range from royalty charges, annual mining fees and renewal charges, artisanal mining license, reconnaissance license, exploration license, large and small scale mining license (**Figure 1**). In addition, surface or land rent and lease agreement provide revenue for land holding families and the community in general. To enhance sustainable community development, large scale mining license holders are obliged to engagement in development activities within the mining community upon reaching a certain production level.

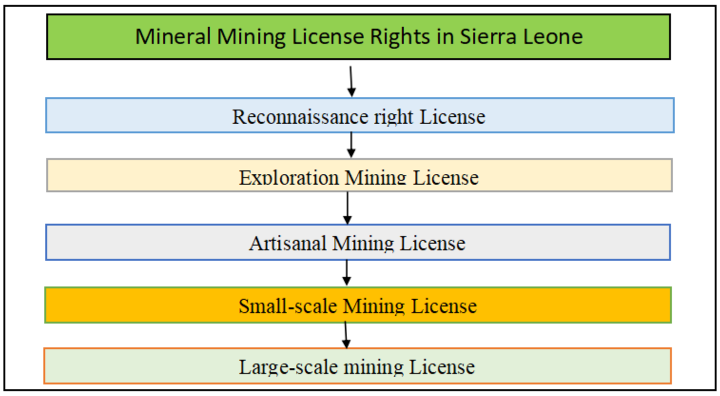

Figure 1. Mineral mining license right in Sierra Leone.

Critics however argue that, the abundance of mineral resources in Sierra Leone has not translated into economic growth or sustainable development, but has instead resulted into poverty for some mining communities since the commencement of mineral extraction in 1930 [30,31]. Instead, Sierra Leone is among the least develop nations globally with high poverty rate and low standard of living. According to the Truth and Reconciliation Commission report [32] mineral resources mismanagement was among the root causes of the bloody 11 years' civil conflicts that ravaged Sierra Leone for a decade. In such, opinions vary among citizens on weather mineral resources of Sierra Leone are a "Resource curse" or a blessing to the nation [2].

4.1. Mineral mining and its social and environment related issues in Sierra Leone

Globally, mineral mining has contributed to the improvement in the standard of living of both developed and developing countries [33,34]. However, the mineral sector in Sierra Leone is faced with numerous challenges due to outdated mining laws and regulations that fall short of meeting international standards in the 21st century [6,17]. On the other hand, mineral mining in Sierra Leone has supported rural livelihood drive and national development agenda over the past decades. For instance, big mining companies like the Koidu holdings Ltd and Sierra Rutile has supported education, built local clinics, support sporting activities and engage in infrastructural development within their operational territories. However, the social injustices associated with mineral mining in Sierra Leone and in other parts of the world has been considered a global concern and is attracting huge global debates [35] especially in meeting the sustainable development goals.

Mineral mining has been regarded as the root to biodiversity decline and is regarded as the major threats to sustainable ecosystem function and biodiversity increase [9,16]. Both artisanal and large scale mining are engaged in clearing a large aspect of vegetation for their operations. Mining activities are destroying viable forests ecologies, riparian zones, and coral reefs that harbors varieties of wildlife and other forms of biodiversity [9]. Artisanal mining activities like sand and stone mining being practiced along coastal ecologies like the Freetown peninsular area has resulted in devastating beach erosion and aquatic ecologies alterations. Swamp ecologies have been converted to artificial ponds after dredge mining activities in Moyamba District [36].

Environmental pollution is also a bye product of mining activities across Sierra Leone. Most mining communities suffer from water and land pollution due to mining operations [37]. Traditional sources of pure drinking water have been contaminated and in some cases destroyed. Ground waters has been polluted by heavy machineries and oil spillage in some mining communities due to leaching. Mining in some communities disrupt the water drainage system and create irregular heaps across mined landscapes [6]. For instance, the Kimberlite mining processing practiced by the Koidu Holding Ltd in Kono District includes sites bombardment that mostly results in large artificial pits and the destruction of soil structure, composition and biodiversity [38]. In Kono District, mineral mining is considered a controversial investment with both positive and negative face.

In a nutshell, good drinking water is a fundamental problem in most mining communities in Sierra Leone. Mining activities don't only affect the immediate mining community but the downstream communities equally suffer from polluted water. For example, the Taia River in Moyamba District has change color due to mining activities being undertaken upstream by miners. The water quality in theses mining sites is deteriorated and sometime serve as mosquito breeding ground [6]. Similarly, dust and noise pollution have been reported in mining edge communities [39]. Mining areas in Sierra Leone are characterized by poor health and sanitary conditions that has eventually resulted in blindness and disability. Also, the constant noise produced by heavy machineries working in close proximity to mining towns and villages have left many local residents deaf [40,41]. Most mining communities in Sierra Leone lack essential drugs and hospital for treating chronic cold due to artisanal and illegal mining.

Other human right abuses portray by mining activities in Sierra Leone is child labor. Across mining communities in Sierra Leone, children from age 7 to 18 play active role in mining activities especially the artisanal and illegal mining operations. Parents and local investors use them as cheap unquestionable labor hence forcing them to drop out of normal school [15]. There is more premium place on mining activities in mineral rich communities across the country than education and other works of life. Another social issue driven by mineral mining is early marriages and teenage pregnancies. However, most of these early marriages and teenage pregnancies are associated with either poverty or sexual offences like rape among others [42]. The influx of young men in search of greener pasture in mining communities expose these areas to all caliber of criminals and human rights violators. These young miners take advantage of poor young girls and prey on them either deceitfully or forcefully.

4.2. Mining as a catalyst behind the civil war and social unrest in Sierra Leone

According to a study done by Ballentine and Sherman [43], a strong correlation was detected between natural resource abundance and arm conflict risk in developing countries. According to Kamara [44], the root cause of the civil conflict in Sierra Leone was diamonds, diamonds and diamonds. The term “blood diamond” from Sierra Leone is prominently featured across African and the world at large [45] based on the atrocities committed for diamond during the civil war. Fearon [46] also noted that mineral resources such as oil makes a country prone to civil conflict. However, institutional failure and corruption are sometimes regarded as the vehicle for arm conflicts and violence in resource rich countries like Sierra Leone [47]. Unlike other natural resources like oil and natural gas that requires sophisticated extraction techniques, diamonds are considered lootable resources that need little or no skill to extract. This characteristic made diamonds looting and smuggling by conflicting factions in Sierra Leone very easy as they had enough labor and the resource is portable [31,36]. Scholarly investigators have stated that, the simpler and lootable a natural resource, the more likely the resource will be of great benefits to fighting factions in a country [31,36]. The United Nations after careful consideration concluded that, illegal diamond mining across Sierra Leone played a great role in fueling and lengthening the civil war in Sierra Leone and Angola [48]. In such, Diamonds were the principal source of income and foreign exchange the

Revolutionary United Front (RUF) depended on to fuel the war for a decade. Mineral mining in Sierra Leone gained political recognition from the colonial era but the over reliance on the resource after independence in 1961 for economic development and political gains makes mineral mining a force to reckon with in terms of political stability and national security [49]. Mining communities are synonymous to social unrest in Sierra Leone over the past decades. These social unrests have caused major socio-economic problems, community instability and social disruption particular in mining communities [50]. Although article 138 of the Mines and Mineral Act 2009 requires mining companies to invest, rehabilitate and contribute to the socio-economic development of mining communities, however, the social unrest in these communities takes precedent over these legislative intentions [51]. The civil unrest in Sierra Leone wouldn’t have lasted for 11 years without the aid of illegal diamonds sold in exchange for weapons and other warfare logistics. The proceedings from these minerals strengthened the rebels, gave them more power as well as political recognition [37,52].

The 2012 and 2013 boom in Iron Ore, Rutile and Bauxite industry in Sierra Leone did not only contribute to economic development but serve as source of tension, conflict and protest across mining communities in Sierra Leone [37,41–43]. Across Sierra Leone, the epicenter for conflicts and frequent community skirmishes between local resident’s and security forces mainly emanate from mining communities [2]. Mining communities are characterized by frequent tensions between unemployed youths and company’s security forces. One notorious destination for mineral mining related confrontations and skirmishes between mining entities and their local counterpart in Sierra Leone is Koidu City, Kono District. Koidu City has been the epicenter for diamond mining since 1930 and has been the place where the biggest diamonds in the history of Sierra Leone located. In 2007, confrontation between Koidu holdings and protesters left two community members dead. This violent protest led to the besieging of the company foreign staff and kept under house arrest at their quarters BBC New [53]. Also, the Tonkolili Iron ore company was accused of multiple human rights abuses in 2010 and 2012 respectively [54]. Similar on 16 April 2012, confrontation occurred between aggrieved workers of the African Minerals Ltd Bumbuna and the police force leading to the death of one woman and injuring eight others severely [55–57].

4.3. Nexus between mineral mining extraction and internal displacement

A clear nexus exits between mineral mining extraction and forceful displacement or relocation in Sierra Leone. Displacement and resettlement due to mining is the process of relocating people affected by the mining operations from their original place of living to another location [38]. Since the inception of mineral mining in Sierra Leone, displacement and resettlement have been the fate of communities located where these minerals have been located. This process however has its consequences on cultures, norms, religion and the way of life of these poor communities. Besides the environmental damage caused by mineral mining, socioeconomic woes as well as social disruption is the order of the day for some mining edge communities in Sierra Leone [38]. What is most appalling is being the forceful and involuntary displacement of people from their place of birth where their great ancestors lived and called home. Although some amount of compensations is given to help affected individuals restore their livelihood and start a new life, nevertheless, these incentives can't replace their ancestral home and place of birth [49]. According to Peligal [58] local resident's rights to water, land and livelihood was not only impeded but local residents and their families were forcefully evicted and relocated to an arid and harsh location around Bumbuna. This forceful relocation of local residents had adverse effect on their livelihood, food security, culture, norms and health. For instance, three villages namely Ferengbeya, Wondugu and Foria in the northern part of Sierra Leone were unwillingly relocated to pave way for Iron Ore mining in their former villages. In most cases, displacement due to mineral extraction has resulted to continual social and economic impoverishment hence exposing local resident to abject poverty with time [38]. In villages like Kanga and Madina in Bonthe District; Ferengbeya, Wondugu and Foria in Tonkolili District and Koidu in Kono District displacement or relocation contributed to sustained impoverishment with reference to basic livelihood amenities. Besides displacement and relocation, internal migration or influx of young men seeking employment has created more problems than mining communities can handle in Sierra Leone. These job seekers have been accused of various human right abuses and theft. Additionally, they are accused of being super spreaders of sexually transmitted disease, impregnating young girls, breaking of social cohesion and religious norms. In such, mineral mining in Sierra Leone is intricately connected and characterized with unwanted displacement or forceful relocation with meagre compensation.

4.4. Economic implication of mineral mining in Sierra Leone since 1930

Since the inception of mineral mining in 1930, revenue generated from the sale of these minerals has played an active role in supporting economic development in Sierra Leone. From 1930 to date, mineral resources have been the main source of foreign export from Sierra Leone [2]. The mining sector provides employment, taxes and other dividends that help facilitate diverse development projects that seek to provides services such as schools, education and other basic amenities. The 1972-star diamond found in Kono District weighed 968.9 carat and placed Sierra Leone on the spot light of mineral rich countries. This diamond was the third biggest diamond ever found on earth and was discovered in Kono. Similarly, a 709 carat diamond was found in 2017 and was class among the twenty biggest diamonds ever found [2,44,50]. Subsequent governments after independence remained deeply dependent on mineral resources proceedings to undertake various economic development activities across the country. Recent Statistics shows that approximately, 400,000 people are being employed by the sector between 2012–2013 and constitute 80% of foreign export [39,51]. If good mineral mining fiscal policies are put in place, the sector has the capacity of serving as the main engine of socio-economic development in Sierra Leone [58]. Mineral mining, stone and sand mining has equally been a major source of employment and by extension income for most uneducated youth in Sierra Leone. Mineral resources remained the main source direct foreign exchange and source of export over the past decades [5]. For instance, artisanal diamond mining and export is dubbed a critical prosperity driver in Sierra Leone and employs thousands of unskilled labor.

Besides surface rents, royalties, license fees and other source of revenue received from mining companies in Sierra Leone, most companies like the Koidu holding Ltd, former African Minerals, Sierra Rutile Ltd among others have satisfactorily undertaken various cooperate social responsibility (CSR) in the form of building clinics, markets, schools, community centers, providing safe drinking water, giving scholarships etc. The provision of these facilities has positively influenced the socio-economic and livelihood pattern of mining community residents over the years. Similarly, scientific evidence has shown that, there is a great boom of business exchange/ activities in mining territories as compared to non-mining territories. Within mining communities in Sierra Leone, petty trading is financially beneficial and yield great dividend over time. Mining activities especially in mineral rich communities has stimulated internal migration of energetic youth from remote parts of the country to mining areas [5].

4.5. Mineral mining and livelihood security in Sierra Leone

Sierra Leone is a low income country thereby making its livelihood un-insure in diverse ways. Mineral mining can serve as a mean of sustainable livelihood booster for mining edge communities in Sierra Leone if international mining standards are adhered to and applied. The emergence of mineral mining in Sierra Leone between 1920–1930 have had mix reaction about their contribution to livelihood. Mineral. However, mineral mining especially in Sierra Leone has made residents of nearby communities vulnerable to various health risk and uncertainties. Nonetheless, some communities in Serra Leone enjoy better economic conditions from the Cooperate Social Responsibility (CSR) scheme of most mining companies. The CRS scheme seek to positively contribute to the social, economic, and environmental benefits of host communities for sustainable development [52]. The CSR scheme makes sure that mining companies take full responsibility for their imprint on mining societies. Over the years, mineral companies have made socio-economic contributions to society in the form of built community centers, hospitals, clinics, schools, water taps, resettlement buildings, feeder road maintenance and educational scholarship among others. These activities support rural livelihoods and enhance sustainable socio-economic development in some from Although mineral mining has negative foot print on the environment, yet still, its contributions have in some ways benefited locals in their livelihood quest.

Mining has over the years had both positive and negative implication on the livelihood of mining edge communities in Sierra Leone [53]. Scientific literature suggests that mining affects the livelihood of communities directly or indirectly in Sierra Leone [38,59]. One fundamental source of livelihood support provided by mineral mining is direct employment of community members living within mining communities. Across Sierra Leone, employment within the mining industry support livelihood activities through salary and income earned from mining work. These earning are mostly above the average income earn by farming or other livelihood activities undertaken in most mining communities in the country. In most cases, livelihood enhancement is stimulated by type of mining activities practice in a community. While large scale mining employ plenty workers, artisanal and small scale mining contributes more to rural livelihood due to the volume of local inhabitant employ or involve in the process [5].

4.6. Mineral mining implication on biodiversity conservation

In Sierra Leone, mineral mining has been proven to be the major cause of flora and fauna loss as well as environmental degradation on a large scale [2]. Loss of natural ecosystem/habitat through mineral mining is considered the biggest reason behind biodiversity loss in mostly mining landscapes hence making the future of biodiversity increase uncertain [60]. The socio-economic and environmental implication of mineral mining have dominated the global discourse of major causes of biodiversity loss for decades [58–60]. The impact of mining is mostly felt at international, regional, local and individual level around the world. Mining and its related implication on biodiversity conservation is a hot global discourse that has attracted both decision and policy makers around the world. Mining activities though financially beneficial, it is however subjected to environmental pollution and biodiversity loss. Across Sierra Leone, mining has destroyed and continue to degrade mining ecologies nearby communities. Mining is a crucial sector in the sustainable development of any nation as well as the source of income that supports human survival. Nonetheless, its negative impacts on ecosystem and biodiversity cannot be underestimated especially in a developing country like Sierra Leone [61]. Besides biodiversity loss impact of mining, mining result to landslides, soil pollution, erosion, ground water contamination, disease outbreak and degradation [62]. In mining communities, forests ecosystems have been cleared, biodiversity affected and the environments altered permanently. Most wildlife in mining areas around Serra Leone are mostly forced to migrate to unsuitable environment where they are faced with survival risk. As a results, most wild animals once occupying mine areas has gone into extinction. Some wild animals have migrated to neighboring countries were mining activities and ecosystem destruction is minimal. This migration has led to the disappearance of valuable and important animal’s species from Sierra Leone. In such, mining activities has place huge pressure on biodiversity increase with the problems showing no signs of abatement any time soon in Sierra Leone. In forested communities across Sierra Leone, biodiversity conservation plays an integral role in enhancing rural livelihoods, protecting traditions and norms, improving the quality of life, contribute to national economy development and improve eco-tourism.

4.7. Mineral mining influence on climate change uncertainties

The mining sector is becoming increasingly vulnerable to climate change especially in a developing country like Sierra Leone. This could be attributed to the fact that mining is energy intensive and a good emitter of greenhouse gases [63–64]. It is estimated that the mining sector account for 2% to 3% of emission emanated from global carbon and its play an important role in the greenhouse gas emissions. In such, mineral mining tends to have both direct and indirect effects on climate change uncertainties and vulnerability over a long period of time [65]. The negative impact of the mining sector in Sierra Leone goes far beyond biodiversity loss and extend to climate change vulnerabilities and uncertainties. There is a clear connection between the mining sector and climate change vulnerabilities in countries like Sierra Leone. Although Sierra Leone is not an advance industrialized country, however, it shares greater portion of climate risk as a result of unsustainable mining being practiced throughout the country. Sierra Leone is among the nations that lacks active climate change adaptation strategies but has large mineral extraction capability with great climate risk and uncertainties [66]. Moreover, high dependence on natural resources like minerals couple with unsustainable and weak mining policy enforcement render Sierra Leone extremely vulnerable to climate change impact and risk [67]. The continued environmental degradation of mined ecologies in Sierra Leone exposes the country to climate-induced risk and uncertainties [68]. Climate change is not the only risk associated with mineral mining in Sierra Leone but fishes and people are equally vulnerable to climate change risk posed by mining activities in Sierra Leone [69–70].

The mining sector especially the artisanal sector contributes to massive environmental degradation and at the same time influence the micro-climate of mining communities in Sierra Leone [71–75]. In recent times, mineral mining equipment installation operation and performance have been impacted by extreme climatic events in mines sites across Sierra Leone [76–80]. The sustainability of the mining sector is heavily dependent on the ability of a nation to devised a suitable climate risk, uncertainties and vulnerability. A sustainably mined sites help improve the environment and by extension the climate of the surrounding area.

5. Conclusion

Although Sierra Leone is endowed with abundant natural resources, yet its extraction and management is characterized by socio-political tension and unrest in mining communities. Across Sierra Leone, the loss of natural ecosystem/ecologies through mineral mining is considered the biggest motive behind biodiversity loss in mining landscapes in Sierra Leone. The review discovered that mineral mining has both positive and negative impact on the sustainable livelihood of mining societies in Sierra Leone. The positive aspect entails the socio-economic development contribution in the form of clinics, scholarships, community centers, agricultural support etc. On the other hand, the negative aspect comprises of environmental degradation, environmental and noise pollution, biodiversity decline, and landscape fragmentation. Mineral extraction has over the years resulted to coarse internal displacement of local residents. This forceful relocation of local residents has had adverse effect on their livelihood in the form of, culture, tradition, food security, norms, health and belief. Since independence, Sierra Leone has enacted a plethora of mining reform and these reforms are in the form of institutional reforms, mining agreement criteria, established mining policies, mining community financing, environmental protection improvement measures, environment impact assessment and licenses among other reforms. However, the review concludes that, Sierra Leone is still far away from judicious managements of resources earned from mineral mining for the benefits of the country and could be attributed to rampant corruption, weak policy implementation and loopholes in some mining policies. The adoption of best internationally adopted standard on mineral extraction be introduced in Sierra Leone for the benefits of the environment and the society as a whole. It's recommended that rigorous and unbiased environmental impact assessment be carried to understand the depth of future challenges associated with mining.

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Review

Loss and gain of marine biodiversity in Mediterranean seawaters

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Abstract: The Mediterranean Sea is one of the most important biodiversity hotspots worldwide. The high biodiversity level of the basin is confirmed by the presence of about 17,000 marine species of which 20.2% are endemics. Amongst them, *Posidonia oceanica* (Linnaeus) Delile can form, in pristine coastal waters, large and extensive meadows, performing a pivotal role in endemic processes. However, the richness of marine biota is, actually, affected by some threats such as habitat loss, marine pollution, climate changes, eutrophication and the establishment of invasive alien species coming from the Indo-Pacific region through the pathway of Suez Canal. This trend could lead to a new kind of marine biodiversity influenced by the introduction of termophilic species altering the pattern of Mediterranean biota. Anyway, it is necessary a global approach, ensuring the better ecological conditions so to protect marine biodiversity in meditrranean seawaters.

Keywords: Mediterranean Sea; *Posidonia oceanica*; marine biodiversity; alien species; endemics

1. Introduction

Coastal areas, representing just the 10% of earth's surface, holds about the 60% of world population [1]. The high demographic pressure could increase in the next decades, as urbanization is driving a growing movement of people towards the coast. Really, many services are provided by coastal systems as are: fishing, harbouring, commercial trade and coastal tourism. Besides, the littoral zone is a sensitive area where sea and land interact and play altogether an important role, integrating coastal water and its watershed in a whole system. However, the increasing urbanization of coastal areas, the proliferation of harbours and the realization of artificial barriers, to protect sandy beaches from erosion, are contributing to fragment marine benthic biocenosis altering their natural connectivity and causing a potential loss in marine biodiversity [2]. The Mediterranean, at the crossroads between land and sea, is a semi-enclosed basin connected, at its western side, with the Atlantic Ocean through the Strait of Gibraltar and, at its southeastern side, with the Indian Ocean through the Suez Canal. The special geographic location of the basin and the late doubling of this last waterway, happened in 2015, have favored the flourishing of many termophilic alien species into the basin. So, the Mediterranean Sea, has became, in time, one of the most important hotspot for the marine biodiversity worldwide. Actually, many threats such as habitat loss, marine pollution, climate changes, eutrophication and bioinvasions are affecting the biological diversity of Mediterranean biota. Amongst the main environmental problems, two critical ones are shoreline erosion and biodiversity loss, closely connected, also, in other semi-enclosed basins as the Baltic and the Black Seas [3–5]. Italian coastal regions, with more than 8000 km of their coasts, altered by human infrastructures, are considered the most densely urbanized and populated among the Mediterranean countries [6]. The tight connection between these issues is especially marked along the Western side of the Mediterranean basin where the increased concentration of mineral particles is a real threat to benthic biota.

2. The biodiversity of *Posidonia oceanica* meadows

Posidonia oceanica meadows, in Italian coastal waters, are suffering from silting processes leading to a reduction in their leaf density and to a remarkable increase in the rate of mortality of the leaves, as highlighted, also, for other Mediterranean meadows [7–13]. Really, this negative trend could be caused by erosion and silting processes leading to a decrease in the photosinthetic ratio of the plants. In the whole Mediterranean Sea, Posidonia beds cover a total surface area between 2.5 and 5.0 million of hectares [14] but in these last decades it is possible to highlight, by scientific literature [15], a progressive regression of the meadows variable between 13% and 50%, in regard to the values recorded in 2000. In the basin, the regressive trend of the surface area covered by Posidonia oceanica meadows, could affect other endemic species still living, as epibiota, on Posidonia blades. In fact, *Posidonia oceanica* performs an important pivotal role in the evolution of some endemic species, such as Bryozoan and Hydrozoan sessile epibiota living on its leaves [16–18] (**Table 1**).

Table 1. List of endemic sessile species recorded on Posidonia leaves.

Species	Authors	Phyla	Classes	Orders
Agloiophenia harpago	(Schenk, 1965)	Cnidaria	Hydrozoa	Leptothecata
Campanularia breviscyphia	(Sars, 1857)	Cnidaria	Hydrozoa	Leptothecata
Coryne epizoica	(Stechow, 1921)	Cnidaria	Hydrozoa	Anthothecata
Electra posidoniae	(Gautier, 1954)	Bryozoa	Gymnolaemata	Cheilostomatida
Microporella joannae	(Clavet, 1902)	Bryozoa	Gymnolaemata	Cheilostomatida
Monotheca posidoniae	(Picard, 1952)	Cnidaria	Hydrozoa	Leptothecata
Tridentata perpusilla	(Stechow, 1919)	Cnidaria	Hydrozoa	Leptothecata
Tricolia speciosa	(Von Mühlfeldt, 1891)	Mollusca	Gasteropoda	Trochida

3. Endemics in Mediterranean Sea

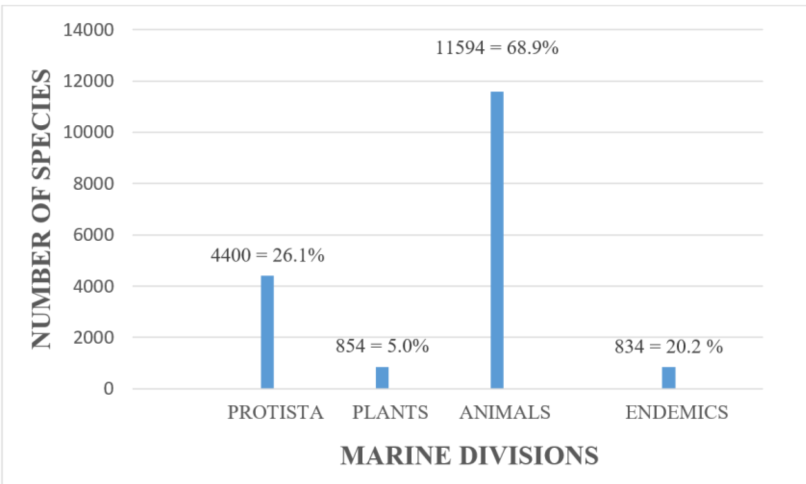

Figure 1. Pattern of Mediterranean marine biota.

The Mediterranean biota is composed by 16,848 species [19] shared out in protista as 26.1%, plants (5.0%) and animal (68.9%) divisions, while the endemic species are estimated about the 20.2% of the whole (**Figure 1**).

The high levels of marine biodiversity in Mediterranean biota derive primarly from the Atlantic Ocean but, anyway, the special variability of climate conditions and the long phylogenetic history of the basin have caused in time the evolution, the diffusion and the establishment of many temperate and endemic species [20–23]. In particular, as regards endemics, their percentages reach a total value of 20.2% distributed in the following divisions: Porifera (48%), Mysidacea (36%), Ascidacea (35%), Cumacea (32%), Echinodermata (24%), Bryozoa (23%), Seaweeds and Seagrasses (22%), Aves (20%), Polychaeta (19%), Pisces (12%), Cephalopoda (10%) and Decapoda (10%) [19] (**Figure 2**).

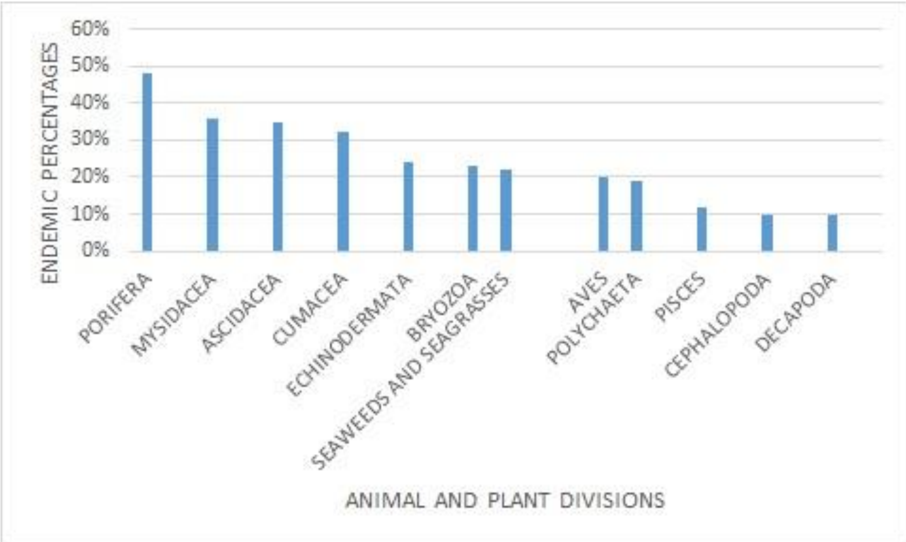

Figure 2. Percentages of endemic species in animal and plant divisions.

4. A new kind of biodiversity

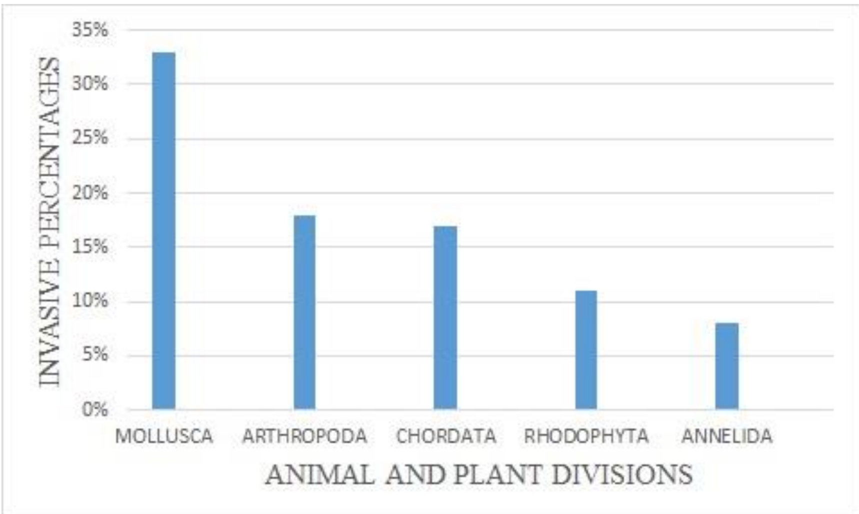

Figure 3. Percentages of Invasive Alien Species in animal and plant divisions.

In these last decades, there is, also, a new kind of Mediterranean marine biodiversity caused by the introduction into the basin of many Invasive Alien Species (IAS) coming from the Indo-Pacific region through the Suez Canal [24–30]. Most of these thermophilic species are littoral and sublittoral benthic organisms belonging to the following phyla: (Mollusca 33%), Arthropoda (18%), Chordata (17%), Rhodophyta (11%) and Annelida (8%) [19] (**Figure 3**).

5. Threats to marine biodiversity

The estimated richness of marine biota shows, actually, a clear decreasing gradient of species and a general drop in biodiversity levels from the northwestern to the southestern regions of the basin [31,32]. Actually, there are many threats affecting marine biodiversity in Mediterranean Sea. According to Lotze et al. [33], habitat loss is the main risk factor (76%) followed by exploitation (54%), pollution (49%), climate changes (38%), eutrophication (35%), bioinvasions (25%), maritime trafic (12%) and aquaculture (10%) (**Figure 4**).

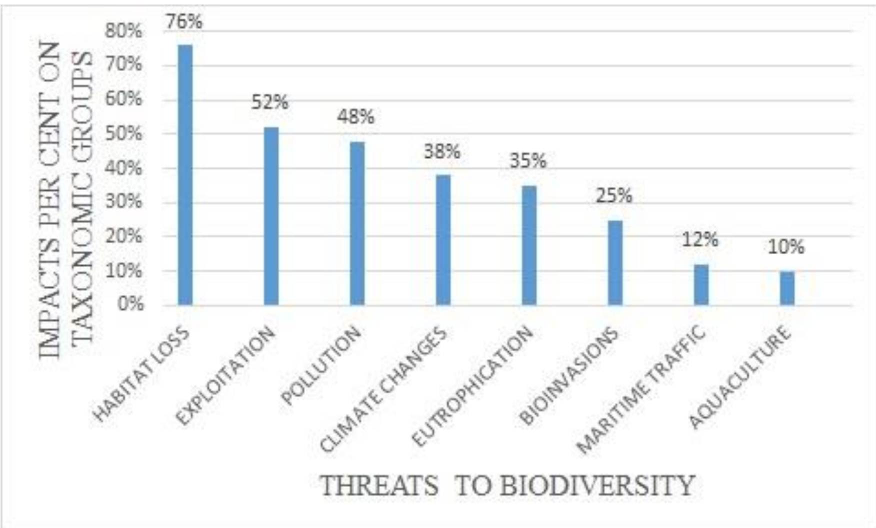

Figure 4. Percentages of risk categories threatening marine biodiversity in Mediterranean Sea ([19], modified).

These values are drawn from published data and scientific opinions by experts for 13 taxonomic groups very sensitive to the present threats affecting marine biodiversity [34]. This trend is expected to grow in the future, affecting a great number of taxonomic groups and endemic species, so leading to important changes in the functioning and in the structure of coastal ecosystems.

6. Conclusions

The study shows a marine region characterized by high biodiversity levels and by a great diversification of species but there is an urgent need of further studies in some marine areas largely unexplored such as the African coast and the deepths of the Mediterranean basin. This report shows the high complexity of Mediterranean Sea where natural and human forces interact, affecting marine biodiversity. Really, our knowledge is quite limited and lacking of a real comprehension about how different impacts could interact each other. So, it is necessary a global approach to choose the better conservation and management efforts aimed to preserve Mediterranean biodiversity. In conclusion, the protection of the Mediterranean ecoregion can only be achieved by guaranteeing favourable ecological conditions for species, habitats, mankind and ecological processes.

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Communication

Rural technology for green skills and livelihood sustainability in Uttarakhand of Indian Himalayan region

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Abstract: Concerns for the environment in India have led to increasing calls to sensitize youth through Environment Education and strengthen their skills which focus on environmentally conscious sustainable future. Green skilled people with expertise in environment management/conservation along with commitment will help in achieving the sustainable development goals. Uttarakhand region of India harbours rich biodiversity that fulfil the needs of local people. Utilizing the potential of 'Rural Technology' for developing green skills in the region will help in livelihood sustainability in Uttarakhand. This short communication highlights about the opportunities in Rural Technology used for green skills and livelihood sustainability in Uttarakhand of Indian Himalayan Region.

Keywords: rural technology; Uttarakhand; biodiversity; livelihood; local communities

1. Introduction

Concerns for the environment in India have led to increasing calls to sensitize youth through Environment Education (EE) and strengthen their skills which focus on environmentally conscious sustainable future. The significance of EE is now prevailing and youth knows the need of preserving environment for future generation. National Education Policy in India has incorporated EE in its framework. The policy envisions high quality education to all, thereby making India a global knowledge superpower. It is founded on the five guiding pillars of Access, Equity, Quality, Affordability and Accountability. It will prepare the youth to meet the diverse national and global challenges of the present and the future [1] India has a long tradition of holistic and multidisciplinary learning and towards the attainment of such a holistic and multidisciplinary education, the flexible and innovative curricula of all Higher Education Institutions shall include credit-based courses and projects in the areas of community engagement and service, environmental education, and value-based education. Environment education will include areas such as climate change, pollution, waste management, sanitation, conservation of biological diversity, management of biological resources and biodiversity, forest and wildlife conservation, and sustainable development and living. Capacity building of youth for green skills is one of the mandatory requirements of EE on topics like biodiversity, control of pollution, solid waste management, forest conservation etc. For achieving the sustainability of environment along with social and economic perspective, commitment towards nature based activities is necessary [2]. Uttarakhand region of India harbours rich biodiversity that fulfil the needs of local people. Livelihood of people in Indian Himalayan region is dependent on natural resources [3]. The main land use activity in the region is agriculture and is connected to the forests for providing sustainability. Local people's economy is focused on agriculture, animal husbandry, medicinal/aromatic plant cultivation, forest resources and tourism [4]. The people of the region to earn a better livelihood migrate to plain areas in search of employment [5]. This short note highlights about the Rural Technology used for green skills and livelihood sustainability in Uttarakhand of Indian Himalayan Region.

2. Study area

Uttarakhand State in India have diverse landscapes and biological diversity, located at the foothills of Himalayan Mountain ranges. Land area consists of 56.72 lakh ha, major part is under forests and wastelands [6]. It is located between 28°43′N to 31°28′N latitude and 77°34′E to 81°03′E longitude. There are six National Parks, four community reserves and seven Wildlife sanctuaries which forms the protected area network of the region covering 3.24% of its geographical area [7]. The distribution of temperature condition over Uttarakhand varies greatly from −1.7 °C at Mukteswar to 42 °C at Pantnagar [8]. Uttarakhand Action Plan on Climate Change, Government of Uttarakhand indicates that the annual rainfall in the Himalayan region may vary between 1268 ± 225.2 mm and 1604 ± 175.2 mm [9]. The precipitation that has been forecast shows a net increase in the 2030s with respect to the simulated rainfall of the 1970s in the Himalayan region by 60 to 206 mm. The State has presence of rare and diverse species of flora and fauna. Indian Himalayan Region has trans-boundary connection of protected areas i.e. Indo-Nepal border of Kailash and Kangchenjunga landscapes [10]. State has a population of 10.09 million with 16,793 villages according to 2011 census, which is 0.83% of India's population. Rural population is 69.77% whereas urban population is 30.23 [11]. In biodiversity-rich areas, both conservation and socio-economic development are at the core of discussions among various stakeholders [12]. For promoting the improved livelihood of the people in Central Himalaya of India, there are various innovations being conducted along with conservation and management of natural resources. In this context, a study was carried to evaluate the potential of various solutions/innovations that are being implemented in the Himalayas of India [12]. It was found that only a few are found to be successful in both conservation and sustainable livelihood development. The study revealed that people are still looking for more viable solutions that could help them improve their lifestyle, as well as facilitating ecosystem conservation and supporting existing biodiversity.

3. Green skills

International Labour Organisation, defines green jobs as decent jobs that contribute to preserve or restore the environment [13]. It can be in traditional sectors like construction, manufacturing as well as emerging sectors of green field. Such Green jobs facilitate energy efficiency; limit greenhouse gas emissions; minimize waste and pollution; protect and restore ecosystems; and support adaptation to the effects of climate change [13]. United Nation Industrial Development Organisation (UNIDO) states that green skills are the abilities, values, knowledge and attitude which are required for sustainable and resource efficient society [14]. There are four groups of work in UNIDO's Green General Skill Index for green occupations which are as follows:

- Engineering and technical skills: Skills involving design, construction and assessment of technology for eco-buildings, renewable energy design and energy-saving research and development (R&D) projects.
- Science skills: Competences stemming from bodies of knowledge broad in scope and essential to innovation activities, for example physics and biology.
- Operation management skills: Know-how related to change in organizational structure required to support green activities.
- Monitoring skills: Technical and legal aspects of business activities.

Green Skill Development Programme of Ministry of Environment, Forest and Climate Change (MoEF&CC), endeavours to develop green skilled workers having technical knowledge and commitment to sustainable development, which will help in the attainment of the Nationally Determined Contributions [15]. Under the programme, the vast network and expertise of ENVIS Hubs is being utilized for skill development in the environment and forest sector. List of courses includes water budgeting, propagation and management of bamboo, greenbelt development for industries, cleaner production assessment, Wildlife Management using Geospatial Techniques, Emission inventory, Forest Fire Management etc. Mainstreaming such skills shall develop responsible behaviour among society leading to improved environment. It shall imbibe the culture of green skills among the youth by promoting innovations and sustainable technologies.

4. Rural technology complex

G.B. Pant National Institute of Himalayan Environment (GBPNIHE) which is an autonomous institute of MoEF&CC has developed Rural Technology Complex (RTC) in their Headquarters in Almora, Uttarakhand in the year 2001. This complex aims to address the needs of local communities in the hilly areas with respect to the local specific technology interventions. The vision of RTC is capacity building of Himalayan mountainous communities for improving their life by effective management of natural resources and dissemination of knowledge through training on various rural technologies [16]. Village resource mapping and assessment is conducted for collection of village baseline data. Technologies like Pine processing, bio briquetting, polyhouse protected cultivation, vermin-composting, and integrated fish farming are promoted in the region through RTC (**Figures 1** and **2**). Local communities nearby are benefitted from RTC by active participation in the training programmes [16]. Sekhar [17] has indicated that participation of women in the rural economy is significant. Women's development and awareness through education is very important factor. In the Pine needle processing unit of RTC, women groups of nearby villages have been successfully engaged in collection of pine needles. The intervention yielded benefits of i) reducing fire intensity in surrounding Pine forests, and ii) improving livelihoods of local communities. gained popularity for eco-friendly pine needle based products such as file covers, meeting folders, carry bags, envelops, etc. Also, the conversion of pine needles into smokeless bio-briquettes is receiving appreciation of rural masses. This venture, while addressing the issue of forest fire has contributed equally for rural livelihoods promotion by effectively engaging with rural women groups [16]. Livelihood opportunities (**Figure 3**) may also be accessed with the State Government departments like promotion of local product, preparation of handicraft items, promotion of local food items, exploring the potential of ecotourism in adjacent areas, etc.

Figure 1. Vermi-composting rural technology in the region which replenishes soil fertility.

Figure 2. Shadenet house in the area which protects crops from harmful ultraviolet.

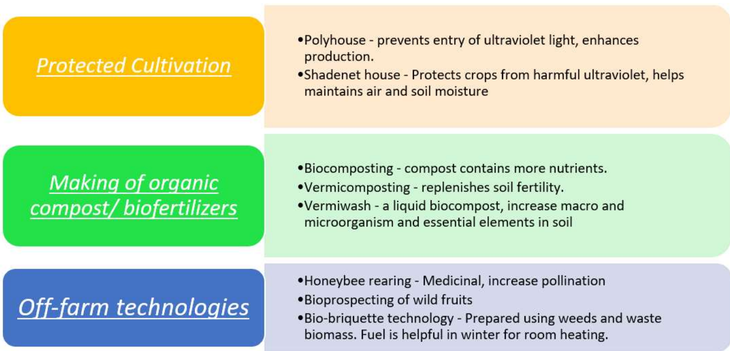

Figure 3. Opportunities in rural technologies for the region.

5. Conclusion

Agriculture is the main economic activity in the region and such technology parks shall provide the desired solutions to upgrade the livelihood of locals and as well as protect the environment of region. Moreover, it can provide better direction for sustainable development of the hill regions for better quality of life. Environment stewardship shall lead to think about the sustainable use of biological resources and ensuring their active participation in natural resource management that caters ecosystem functions and services. It shall also develop the skills of local people and promote a culture of entrepreneurship in rural areas by adopting clean green technologies in various sectors. As rightly said by Padma Bhushan Dr. Anil P. Joshi that true capital of a nation is its natural resources and such parks would strengthen the green skills in the region and further contributing to rural economy. It will also help in controlling the migration of locals for jobs/livelihood. Further in future, detailed research may be conducted to analyse the impact of green jobs in the region that would be of paramount importance.

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