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Advancing Sustainable Water Management Through Research and Innovation: Bridging Knowledge to Impact

LIMNOTEK transforming into Journal of Limnology and Water Resources (JLWR) continuous to focus on establishing an integrated understanding of the interface between natural water processes, inland aquatic ecosystems, and human interactions.

In this 2025 volume 2 issue, we are proud to present a collection of five research articles and reviews that explore critical and interconnected aspects of limnology and water resources. Topics covered range from ecological assessments of key coastal and freshwater habitats to global trends in environmental technology. Two studies highlight the ecological significance of Indonesian aquatic systems: one investigates the role of Siombak Lake as a nursery and feeding ground for estuarine species in the Belawan area, while another examines the diversity and abundance of *Scylla* mangrove crabs on Jambu Beach in Dompu Regency. A bibliometric analysis provides insights into the development of diatom research, particularly in oxbow lake ecosystems, while another global review traces two decades of progress in ecotechnology for textile wastewater treatment. Completing the issue, an integrated field-theoretical evaluation offers a detailed examination of sediment pond efficiency within a tropical mining catchment, underscoring the importance of sediment management in disturbed landscapes. Together, these studies reinforce our commitment to advancing sustainable and science-based water resource management across diverse inland water systems.

Aligned with our vision of continuous learning, innovation, and collaboration, we hope this volume provides valuable insights for researchers, scholars, practitioners, the publics and policymakers to join us in advancing the sustainable use and management of lakes and water resources.

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Cover Image: Lake Hanjalutung, an oxbow lake in Central Kalimantan, Indonesia. Image courtesy of Prof. Dr. Tri Retnaningsih Soeprobowati (Cluster for Paleolimnology – CPALIM).

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Ecological Role of Siombak Lake as a Nursery and Feeding Ground for Aquatic Species in the Belawan Estuary, Indonesia

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Abstract: Tidal lake is a coastal lake whose water condition is influenced by the dynamics of tides. This lake serves as a habitat for a diverse array of aquatic biota, including freshwater, brackish, and marine species. This study aims to describe the distribution of larvae, juveniles, crustacea, and adult fish in the context of the coastal lake's role as a nursery and feeding ground. The study was conducted from September 2018 to August 2019, at Lake Siombak, a coastal lake located in the Belawan River estuary along the northern coast of Medan City, Indonesia. Data were collected at high and low tides during the full moon. Larva and juvenile fish? sampling used larval nets with a mesh size of 300 µm and a diameter of 60 cm, while adult fish were caught with gill nets with a mesh size of 1 inch and a dimension of 10 × 2 m. Crustaceans were captured with traps. The research found nine families consisting of six fish families, two crustacean family, and one cnidarian family. The abundance of larvae and juveniles found was 17 to 1797 individuals per 100 m^{-3}. At the high tides, the composition of Ulmaridae (jellyfish: *Aurelia aurita*) that was caught reached 57.7%. While at low tides, there were more Penaeid families in the Mysis phase, reaching 78.6%. The abundance of Mysis (Penaeid) and jellyfish indicates that the lake serves as a nursery ground for post larvae crustaceans and jellyfish. The presence of adult fish migrating from the sea and Belawan River indicates that the lake functions as a feeding ground in the Belawan estuary. Therefore, Lake Siombak still plays a crucial role as a nursery and feeding ground for fish, crustaceans, and jellyfish originating from the Belawan River estuary and its surrounding areas. Preserving the sustainability of this lake is crucial to ensuring the continued productivity of fisheries in the Belawan River estuary.

Keywords: Belawan, coastal lake, estuarine, juvenile, larvae, nursery and feeding ground

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1. Introduction

An estuary is a coastal area where freshwater from rivers or streams meets and mixes with saltwater from the ocean. These regions are often characterized by unique ecosystems, with a variety of plants, animals, and microorganisms that thrive in the brackish (partly salty) water. Estuaries serve as important habitats for many species, acting as nurseries for fish and other marine life. They also provide crucial ecosystem services such as water filtration, flood control, and habitat for wildlife (Nybakken and Bertness, 2005; Odum and Barrett, 2005; Wolanski and Elliott, 2016; Hopkinson *et al.*, 2019). The estuarine ecosystem is very important for coastal fishery activities. It is well known that estuaries and other coastal ecosystems (mangroves, seagrasses, and coral reefs) are essential ecosystems in supporting coastal fisheries' productivity and production (Haimovici and Cardoso, 2017; Rangkuti *et al.*, 2017; Berkström *et al.*, 2020; Cheminée *et al.*, 2021; Scapin *et al.*, 2021). The main role of estuarine areas is spawning, nursery, and feeding ground for various fresh and marine organisms (Igulu *et al.*, 2014; Dutta *et al.*, 2017; Gómez-Ponce *et al.*, 2018; Pelage *et al.*, 2021). The estuarine region plays an important role in the survival of many fish species in the larval and juvenile phases. Typically, larvae and juveniles grow and develop in safe areas where abundant natural food is available, commonly referred to as nursery grounds (da Silva *et al.*, 2023; Mocuba *et al.*, 2023; Azrieli *et al.*, 2024; Elston and Murray, 2024).

The extent to which the estuary ecosystem supports coastal fishing operations has sparked a lot of curiosity among experts. Numerous studies on fisheries have been conducted in river mouths or estuaries (Nybakken and Bertness, 2005; Rangkuti *et al.*, 2017). The distribution of larvae, juveniles, fish, and adult crustaceans with regard to coastal lakes as spawning, nursery, and feeding grounds is one of the few remaining features of Indonesia's coastal lakes, or tidal lakes. Since fish larvae are one of the most significant stages of fish life, research on one of their ecological characteristics is crucial as a foundational study for the estuary region's fisheries (Berkström *et al.*, 2020; da Silva *et al.*, 2023; Mocuba *et al.*, 2023; Azrieli *et al.*, 2024; Campbell *et al.*, 2024; Elston and Murray, 2024), including coastal lakes/ coastal lagoon (Ocaña-Luna and Sánchez-Ramírez, 2016; Jaxion-Harm and Speight, 2017; Baptista *et al.*, 2020).

Some tidal lakes in the world include: Lagoa dos Patos and Lagoa de Araruama, Brazil, Lake St. Lucia, South Africa, Coorong, Australia, Lake Songkla, Thailand, Laguna de Terminos, Mexico, and Lake Pontchartrain, USA, Mississippi Sound, USA, and Wadden Zee, Netherlands-Denmark. Tropical tidal lakes themselves are found in Lake Chilika, India; Laguna Nokue, Benin; Laguna Teluk Belukar (Nias-Indonesia), Lake Anak Laut (Singkil-Indonesia), and Lake Siombak in Medan City, North Sumatra Province (Muhtadi and Leidonald, 2025). A coastal lake in poor condition is Chilika Lake in India, where water pollution hurts fish quantity and quality, which in turn has an impact on household incomes. However, this lake still has the highest mega biodiversity for tropical coastal lakes in the world (Mengo *et al.*, 2025). Coastal lakes in Indonesia with fairly good conditions are Anak Lau Lakes (Leidonald *et al.*, 2024). Anak Laut Lakes have higher biodiversity (Muhtadi *et al.*, 2023d; 2025) than Siombak Lake (Muhtadi *et al.*, 2020c; 2022; 2023a) and Teluk Belukar Lake (Hasudungan *et al.*, 2008).

Lake Siombak is a coastal lake located in the estuarine region of the Belawan River, close to Medan City in North Sumatra Province. This lake is distinguished by its unique characteristics and is one of Indonesia's tidal lakes. Lake Siombak is an open lake whose waters are affected by tides from the sea (Belawan-Malacca Strait). This lake has an area of 29 ha. Like other coastal lakes, Lake Siombak is one of the shallow lakes. The average lake depth ranges from 2.96 - 5.26 m when it rains and 2.96 - 4.90 m when it is dry. This lake is a type of tidal lake. Tidal characteristics in Lake Siombak are semi-diurnal, which means that there are two high tides and two low tides, with the height relatively the same. Tidal measurement results in Lake Siombak showed that the highest water level elevation (HAT) is 2.66 m during rain and 2.23 m during the dry season. The lowest water level (LAT) is -0.43 m during rain and -0.04 m during the dry season. Tidal elevation differences that are relatively high (> 2 m) indicate that the lake waters are very dynamic (Muhtadi *et al.*, 2020a). Some parts of the lake are bordered by mangrove forests with varying densities, ranging from sparse to moderate (Leidonald *et al.*, 2019a; Muhtadi *et al.*, 2020b). A range of freshwater, brackish, and marine species, including fish, shrimp, crabs, and shellfish, inhabit the lake (Yulianda *et al.*, 2020; Muhtadi *et al.*, 2022; Muhtadi *et al.*, 2023a). These environmental conditions likely make Lake Siombak an important nursery for various larvae, juveniles, and small fish, as well as a feeding area for adult fish. Thus, this study aims to gather insights into the presence and distribution of larvae and juveniles in this lake, focusing on its role as a nursery and feeding ground for fish and other organisms. Such information is crucial for effectively managing fisheries resources in the Belawan River estuary.

2. Materials and Method

2.1. Study Area

This research was carried out in Lake Siombak, Medan City, North Sumatra Province, Indonesia. (Figure 1), from September 2018 to August 2019. There are 11 observation points consisting of 8 points in the lake (St 1 to St 8) and 3 points in the river (St 9 to St 11). Point 8 is the inlet and outlet of the lake. The fish ponds around (north, St 4 - St 6) enter the lake through St 5. The selection of St 9, St 10, and St 11 is based on the consideration of the existence of a small river, called 'paluh', as the closest comparison to the lake, which still contributes, especially to the water quality of the lake. The detailed conditions of the observation points are presented in Table 1. The sampling was conducted during both high and low tides, specifically every month at the peak of the full moon.

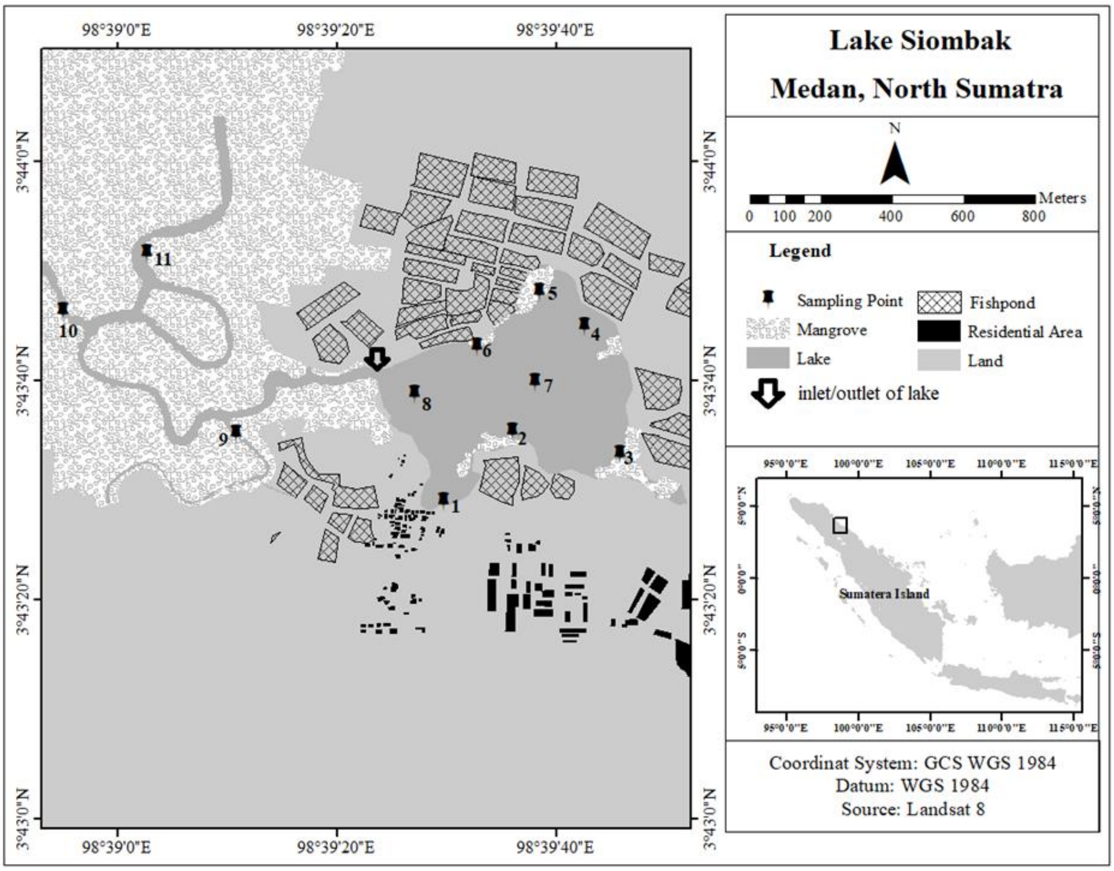


Figure 1. Map of the study area showing 11 observation points

2.2. Sampling of environmental conditions

Water physicochemical parameters, including temperature, salinity, dissolved oxygen, pH, water currents, and water depth, were directly measured in the field during sampling. Temperature and dissolved oxygen were measured by a DO meter (Pen DO meter Lutron), salinity was measured by a refractometer (Atago refragtometer), pH was measured by a pH meter (Atago pH meter), and current velocity was measured by a current meter.

2.3. Sampling of larvae and juveniles

Larvae and juvenile samplings were conducted using larval nets with a mesh size of 300 μm and a diameter of 60 cm. The nets were mounted and secured to the back of a motorboat, positioned 10 m away from the boat at a depth of approximately 0.5 m. The net was then towed horizontally at a boat speed of 1.5 knots for 10 minutes. Afterward, the boat was stopped, and the net was retrieved to collect the samples. The samples collected from the study site were then sorted to separate the larvae, juveniles, eggs, and other materials, such as debris, that might have been captured during sampling. Once sorting was complete, the samples were placed in sample bottles and preserved in a 10% formalin solution. After 24 hours, this was replaced with 70-80% ethanol. Finally, the larvae and juvenile samples were observed and identified in the laboratory Aquatic Environment Laboratory, University of North Sumatra to the most likely taxon. Identification was performed using a microscope equipped with a camera and an ocular micrometer Hirox HRX-01 Digital Microscope to measure the body length of juveniles. Morphological characteristics were examined for larvae identification, which was conducted at the family level using the Leis & Carson-Ewart method (Leis & Carson-Ewart 2004).

Table 1. Characteristics of the observation sites in the Siombak Lake ecosystem

Loca-tions	Mangrove density (tree/ha)	Mangrove conditions	Additional information
St 1	150	Low density	Lake
St 2	250	Low density	Lake
St 3	1,533	high density	Lake
St 4	300	Low density	Lake
St 5	1,200	Medium density	Lake
St 6	150	Low density	Lake
St 7	-	-	Middle of the lake
St 8	150	Low density	Inlet and outlet of lake
St 9	2,500	High density	River
St 10	1,400	Medium density	River
St 11	2300	high density	River

2.4. Adult fish and crustacean sampling

Adult fish were captured using gill nets with a mesh size of 1 inch and dimensions of 10 × 2 meters, while shrimp and crabs were trapped in 1 × 0.5-meter traps placed on the lake bed. Additionally, adult fish, shrimp, and crabs were counted and then dissected for food (gut) analysis and gonad maturity assessment.

2.5. Data Analysis

Calculation of larva and juvenile abundance was done using the modified formula of APHA (2017), as follows:

$$N_i = \frac{C_i}{V} \times 1000$$

where,

Ni = abundance of to-i larvae and juveniles (fish/1000 m^3)

Ci = number of i-th juveniles counted

V = volume of filtered water (Vtsr = *l* × *t* × *v*), with, *l* is the width of the mouth opening of the larval net, *t* is larval net withdrawal time (minutes), and *v* is the pull/tow speed (m/min).

3. Result and Discussion

3.1. Habitat Characteristics

Spatially and temporally, temperature and pH are the most stable water quality parameters in the waters of Lake Siombak during high and low tides. The temperature ranged from 28.4 to 31.5°C (St. dev <1) and the pH ranged from 6.9 to 7.5 (St. dev <0.5) (Table 1-2). In general, the temperature in the tropics is quite stable with low fluctuations. However, at the dry season (Mar-Apr) peak, it shows higher temperatures than other months. In this case, it is suitable for jellyfish conditions, which were found abundantly in March and April.

The pH in brackish waters is relatively stable between 7 to 8.5, and the change (fluctuation) of pH is also relatively small (Odum & Barrett 2005). This finding indicates that coastal lake waters are buffers. Temperature and pH are stable water quality parameters in tropical waters (Sim & Tai 2018). It is the same as in the Akulum Lake, India (Sajinkumar *et al.*, 2017), Chilika Lake, India (Barik *et al.*, 2017), Coastal Bolgoda Lake, Sri Lanka (Ratnayake *et al.*, 2018), and Anak Laut Lake, Singkil, Indonesia (Leidomald *et al.*, 2024) showed stable pH and temperature values throughout the year. However, it is different from Itapu tropical coastal lagoon (Brazil) with more varied temperature and pH values (Raposo *et al.*, 2018). Certainly, the pH and temperature values are more varied than those in coastal lakes in sub-tropical regions (Elshemy *et al.*, 2016; Jamila *et al.*, 2016).

DO values are relatively stable in the waters of Lake Siombak, but at a low range, which is below 4 mg/L. This finding is very different from other coastal lakes with a stable DO value at a value higher than 5 mg/L (Jamila *et al.*, 2016; Barik *et al.*, 2017; Raposo *et al.*, 2018; Ratnayake *et al.*, 2018; Leidonald *et al.*, 2024). This condition is caused by the high organic matter in Lake Siombak compared to other coastal lakes, especially the BOD and COD (Muhtadi *et al.*, 2023b).

Salinity in the lake is quite varied, especially temporally. The salinity value is lower in the rainy season (Sep-Jan and May), ranging from 4 to 8 ‰. While in the dry season (Feb-Aug, except May), the value of salinity is more, which ranges between 6 to 14 ‰. The salinity value is relatively high (> 10 ‰) in March-April, causing jellyfish very abundant in that month. While in the rainy season with low salinity, no jellyfish are found. Spatially, the salinity on the surface of Lake Siombak is almost evenly distributed throughout the lake. This situation indicates that the tidal effect is quite large, affecting the salinity distribution in Lake Siombak. However, the distribution of surface temperatures differs spatially based on the time of measurement. However, vertically, the distribution of temperature and salinity is different between the surface and the lake floor. The temperature on the surface is higher than that on the floor, while the salinity value on the surface is lower than that on the floor (Leidonald *et al.*, 2019b ; Muhtadi *et al.*, 2020a; Muhtadi *et al.*, 2024).

The presence of several larvae and juveniles from the sea entering Lake Siombak is inseparable from the role of Lake Siombak, which provides food in the form of plankton. Other research results by Muhtadi *et al.*, (2020c) show that Lake Siombak is very abundant in phytoplankton and zooplankton larval and juvenile food. This finding is inseparable from the high availability of nutrients in the waters of Lake Siombak. The high nutrients come from rivers and mangrove litter found on the edge of Lake Siombak, and the density of mangroves on the edge of Lake Siombak varies from sparse to dense. The location of the mangrove that is still good (tight) is in the southeast (station 3), while in the north (station 5), it is moderate. The remaining mangroves on the edge of Lake Siombak grow "inline" on the lake's edge. In the forest, "Nipa palm in the Lake Siombak ecosystem can be said to be still good with very dense densities (more than 2000 trees/ha) (Muhtadi *et al.*, 2020b). The existence of mangrove vegetation can also be a protection for fish larvae and juveniles. Andolina *et al.*, (2020), found that aquatic plants in the coastal lagoon could support Sparus aurata larvae's growth in the lake.

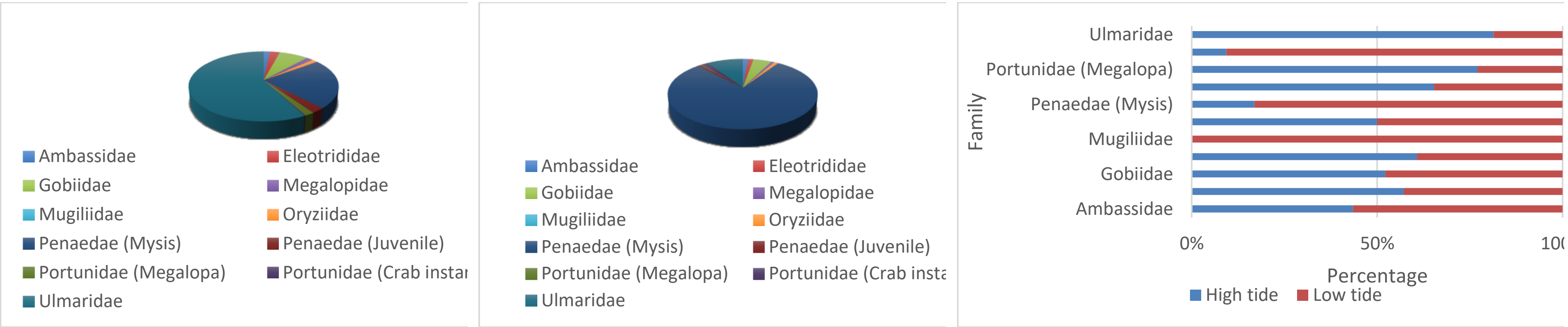
3.2. Composition of larvae and juvenile

Based on the results of larvae and juvenile fish and crustacean research in Lake Siombak, families consisted of 6 families of fish, two families of crustaceans, and one family of Cnidaria. At the time of tides, the composition of Ulmaridae (Jellyfish: *Aurelia aurita*) that was caught reached 57.7%. While at low tides, there were more Penaeids families in the Mysis phase, reaching 78.6%. The number of fish families was mostly found there, in which the crustacean and Cnidaria were dominant during low tides. This condition proves that the estuary area, including tidal lakes, is a nursery ground for crustaceans and jellyfish (Gómez-Ponce *et al.*, 2018; Puspasari & Aisyah, 2018; Fernández-Alías *et al.*, 2020). In general, referring to Figure 2c, it can be seen that crustacean larvae (instar crabs and Mysis) are most commonly found at low tides, whereas in the juvenile phase, including their megalopa, are most commonly found at high tides. Meanwhile, jellyfish larvae are most commonly found at high tides, in which these larvae are carried away when the tides enter Lake Siombak.

Table 2. Temporally water quality in Lake Siombak

Para-meters	**Condi-tions**	**Month**											
		Sep	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Marc**	**Apr**	**May**	**June**	**July**	**Aug**
Salinity	HT	7±2.64	4±1.77	6±1.38	6±1.27	8±2.46	8±2.09	14±1.92	12±1.45	7±2.61	8±2.61	8±2.18	10±2.26
$(^0/_{00})$	LT	6±2.63	7±1.88	6±1.58	6±1.57	10±2.49	8±3.18	13±2.16	11±1.92	8±3.79	6±1.94	6±2.78	10±2.65
Tempe-	HT	30.2±0.52	30.9±0.70	28.9±0.24	29.8±0.34	30.0±0.38	30.0±0.24	31.1±0.60	31.3±0.51	30.4±0.39	28.4±0.54	30.5±0.41	31.2±0.42
Rature (^0C)	LT	30.3±1.37	31.5±1.09	28.8±0.71	29.2±0.34	30.3±0.73	29.5±0.99	30.7±0.42	30.8±0.39	29.7±0.76	28.7±0.70	30.1±0.61	30.7±0.45
pH	HT	7.4±0.21	7.0±0.15	7.1±0.06	7.4±0.31	7.3±0.15	7.3±0.20	7.3±0.15	7.3±0.19	7.2±0.10	7.4±0.17	7.2±0.21	7.1±0.15
	LT	7.2±0.33	6.9±0.16	7.1±0.21	7.2±0.10	7.4±0.27	7.2±0.12	7.1±0.07	7.3±0.16	7.2±0.14	7.4±0.11	7.0±0.09	7.0±0.07
DO	HT	4.8±1.34	4.9±1.27	2.0±0.63	3.2±0.94	4.1±0.60	2.6±0.78	2.8±1.05	3.4±0.83	3.4±1.29	2.6±1.03	2.0±1.09	1.9±0.52
$(mg\ L^{-1})$	LT	5.1±2.62	4.1±2.02	1.9±1.09	2.1±0.79	4.8±1.19	2.6±0.97	1.9±0.62	1.5±0.73	1.7±0.46	2.6±0.80	1.3±0.57	1.0±0.71
Current*	HT	0.24±0.05	0.19±0.06	0.45±0.12	0.75±0.11	0.72±0.11	0.48±0.09	0.38±0.13	0.44±0.12	0.38±0.13	0.22±0.10	0.16±0.03	0.17±0.04
(m/s)	LT	0.43±0.08	0.24±0.06	0.34±0.11	0.23±0.10	0.37±0.10	0.53±0.12	0.48±0.24	0.51±0.25	0.48±0.24	0.19±0.03	0.33±0.19	0.15±0.23

HT = high tide; LT = low tide; * measured currents at part of inlet and outlet (station 8)



a. High tide

b. Low tide

c. Dominant Families

Figure 2. Larva and juvenile composition found in Lake Siombak during (a) High tide, (b) Low tide, (c) percentage Families dominancy

The richness of larvae in Lake Siombak is still higher compared to larvae in Lake Anak Laut, where 10 genera were found. This may be due to the research conducted in Lake Siombak for longer (one year) compared to Lake Anak Laut, which was only 1 month (Muhtadi *et al.*, 2024). Larvae research is mostly done at river mouths. In general, the larvae found in the river's mouth are very abundant in the species' composition (their family). Sixteen Families in Campi Bay (West Nusa Tenggara) (Nastiti *et al.*, 2016), 24 larval species in East Plawangan of Segara Anakan (Cilacap) (Nuryanto *et al.*, 2017), and 13 families in Timbulsoko Village, Demak (Nugroho *et al.*, 2019). However, only seven families were in the Musi River estuary (Prianto *et al.*, 2013), including only six families were in the Jakarta Bay and surrounding areas (Puspasari & Aisyah, 2018). Meanwhile, in tidal lakes or other coastal lakes abroad, data showed that the composition of larvae in Lake Siombak was lower. There are 40 species, 37 genera, and 19 fish families found in the Tamiahua lagoon, Veracruz (México) (Ocaña-Luna & Sánchez-Ramírez, 2016), but not much different from those found in Oyster Bed Lagoon (Honduras) with nine families (Jaxion-Harm & Speight, 2017).

3.3. Spatial and temporal distribution of larvae and juvenile

Spatially, the abundance of larvae and juveniles was highest at station 1, which reached 1797 individual 100m-3 at low tides, and at station 9, which reached 354 individual 100m-3. Meanwhile, the lowest abundance at station 2 is only 17 individual 100m-3 at low tide, and at station 10, which is only individual 100m-3 at high tide. spatially, at high tide larval and juvenile abundance were higher in the northern part (Figure 3), whereas at low tide abundance and juvenile were higher in the southwest (Figure 4). Penaeidae and Ulmaridae are always found at every station during high and low tides. Penaedae, especially shrimp in the Mysis phase, were found to be quite large in Lake Siombak. Mysis abundance ranges from 2-78 individual 100m-3 at high tides and 3-1733 individual 100m-3. Crustaceans, including Penaeid, are marine organisms that make estuaries care areas. After spawning in the middle of the sea, they will be carried by currents into estuaries (Gómez-Ponce *et al.*, 2018). Meanwhile, jellyfish (*A. aurita: Ulmaridae*) are abundant in Lake Siombak. The abundance of jellyfish in Lake Siombak ranges from 2-340 individual 100m-3 at high tides and 1-50 individual 100m-3 at low tides. The abundance of jellyfish in Lake Siombak is higher than in other estuaries.

Temporally, larval and juvenile abundance reaches its peak in the dry season (Feb-August) compared to the rainy season (Sep-Jan) (Figure 5). Jellyfish larvae are only found in the dry season, in which salinity and temperature are higher than those in the rainy season. The peak population of jellyfish larvae is at the peak of the dry season in March, reaching 1548 individual 100m-3 at high tides and 121 individual 100m-3 at low tides. The abundance of A. aurita is influenced by temperature. While jellyfish are more commonly found when temperatures and salinity are high (summer), and during the rainy season, A. aurita was not found (Rahmah & Zakaria 2017; Puspasari & Aisyah 2018; Fernández-Alías *et al.*, 2020). Jellyfish are light-sensitive animals; in sunny weather conditions, the jellyfish will swim horizontally near the surface of the water, and when the weather is cloudy, the jellyfish will swim vertically to the depths away from the surface (Hamner *et al.*, 1994; Suzuki *et al.*, 2019).

Research results in Batu Kalang Beach Tarusan, Pesisir Selatan District, West Sumatra, found that in March, the jellyfish larvae were in the ephyra phase. This month is considered to represent the beginning of the A. aurita season. In May, obtained the medusa phase jellyfish (adult jellyfish) (Rahmah & Zakaria, 2017). In this case, at Lake Siombak the following month after the peak of the dry larvae of jellyfish that will mature into the sea, jellyfish are organisms that prefer salty waters (Puspasari & Aisyah, 2018; Fernández-Alías *et al.*, 2020b). Therefore, (Puspasari & Aisyah, 2018; Fernández-Alías *et al.*, 2020) explain that A. aurita often lives in brackish waters whose salinity is low ± 6 ‰ (larvae) and in open-air ± 30 ‰ (adults).

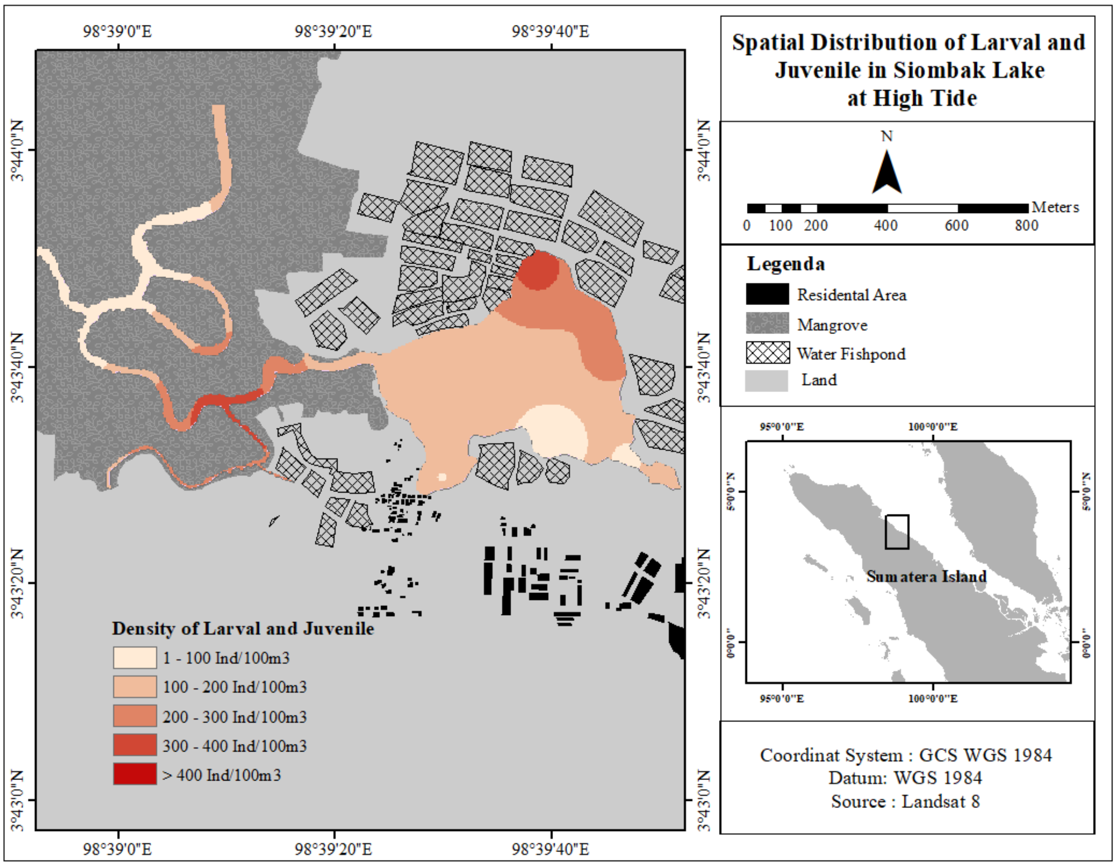


Figure 3. Larva and juvenile spatial distribution in Lake Siombak at high tide

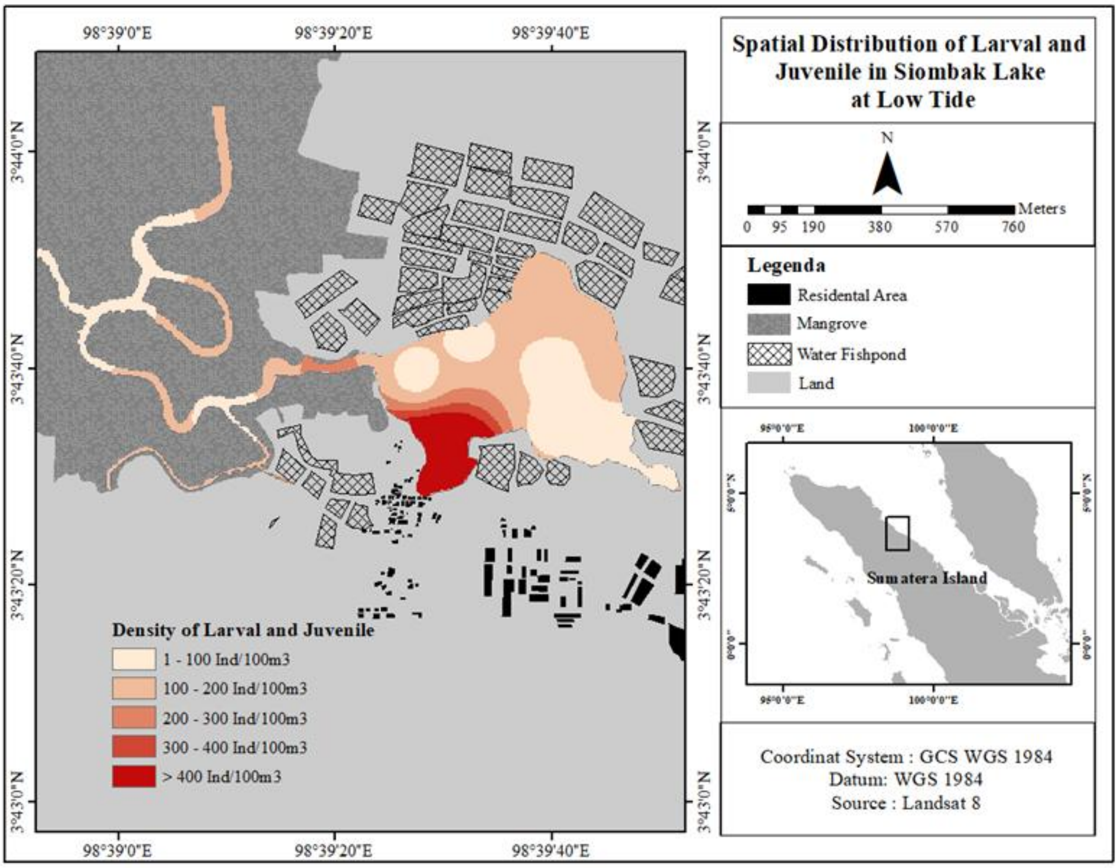


Figure 4. Larva and juvenile spatial distribution in Lake Siombak at low tide

Meanwhile, crustacean larvae (Portunidae and Penaeid) are also more common during the dry season than in the rainy season. Portunidae spawns in the deep sea, where larvae migrate to estuary areas with lower salinity levels to continue their life stage to become mysis and juveniles. This finding was reported by (Kembaren and Suprapto, 2011), that penaeid shrimp larvae tend to move towards the river mouth before metamorphosing to the mysis stages and juveniles. Larvae and mysis need brackish waters and a mangrove environment as a protection area. Mysis and juvenile penaeid shrimp are commonly found in river-mouth environments (Ruas *et al.*, 2019) and tend to like waters with mangrove forests (Jaxion-Harm & Speight, 2017).

Larvae and juveniles found in general are larvae and juveniles originating from marine and originating from the estuary itself (Berkström *et al.*, 2020; Cheminée *et al.*, 2021; Tournois *et al.*, 2017; Mocuba *et al.*, 2023; Elston & Murray 2024). In this study, only the fish larvae of Gobiid and Oryziidae were the larvae originating from Siombak lake. Other larvae are marine species that spawn in estuaries and the sea, then larvae and juveniles are carried by tidal currents into the lake (Berkström *et al.*, 2020). Several fish larvae and juveniles, and crustaceans in Lake Siombak indicate that the lake is a nursery and feeding ground. This is shown by the abundance of mysis crustaceans (Penaeid) throughout the year in Lake Siombak. This condition is compounded by the abundance of jellyfish larvae in the dry season, where jellyfish are very abundant in March-April. This fact is inseparable from the tidal lake in which food is abundant for larvae. The results of previous studies recorded at least 66 genera of plankton, consisting of 54 genera of phytoplankton and 12 genera of zooplankton. Furthermore, plankton in Lake Siombak is very abundant. At the time of plankton abundance, it reached 18.61 million cells m-3 consisting of 15.09 million cells m-3 phytoplankton (81.11%) and 3.51 61 million cells m-3 (18.89%) zooplankton. At low tides, plankton abundance reached 18.20 million cells m-3, consisting of 12.48 million cells m-3 (76.91%) phytoplankton and 3.74 million cells m-3 (23.09%) zooplankton (Muhtadi *et al.*, 2020c).

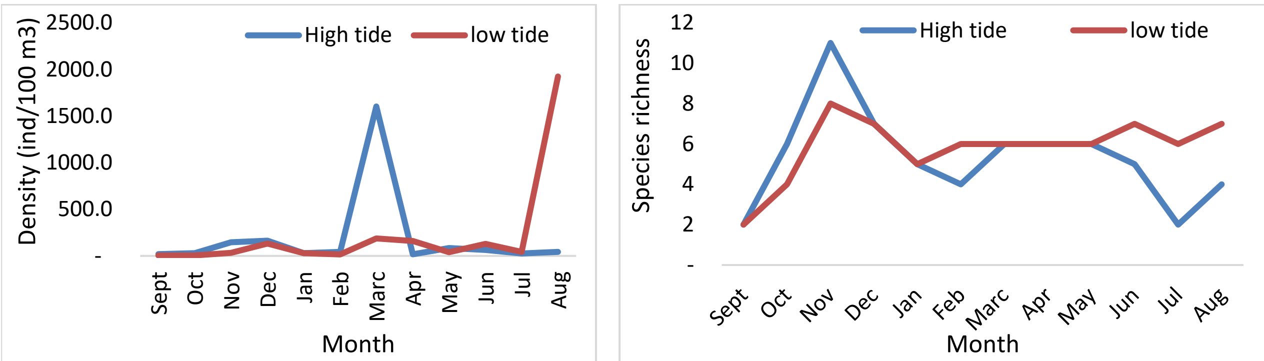


Figure 5. Temporal distribution of larva and juvenile in Lake Siombak

Lake Siombak habitat in the transition area between the fresh and marine ecosystems is possible to visit by both fresh and estuary fish and crustaceans. Based on the previous results study in Lake Siombak, which found that 81.48% of fish and crustaceans found in Siombak Lake are not organisms that settled in the lake. Fish and crustaceans that enter the lake are organisms from the sea (marine organisms) and rivers (new organisms) to the feeding ground (Muhtadi *et al.*, 2022; Muhtadi *et al.*, 2023a). In the rainy season, the fish that enter the lake to feed are freshwater fish, such as snakehead fish, catfish, eels, and Snakeskin gourami. However, during this season, mangrove crabs are also found, namely at stations 1, 3, and 6. Meanwhile, in the dry season, the fish that enter are sea fish, such as gudgeon, snapper, and scat. however, fish such as Indo-Pacific tarpon, marine catfish, and mangrove shrimp are always found in Lake Siombak both in the rainy season and in the dry season (see Table 3).

The main food, based on the analysis of the fish and crustaceans in Lake Siombak, shows that zooplankton is a type of food often eaten by fish and crustaceans by 44.63%, then phytoplankton by 31.07% (Figure 6). Cladocera, Chlorophyceae, and Copepod are the main types of food eaten by fish and crustaceans caught in Lake Siombak, each by 30.51%, 17.80%, and 12.15%. Based on the fish's stomach and crustaceans' analysis, at least 14 fish and crustaceans in Lake Siombak can eat food groups, not including litter and detritus used by mollusks, shellfish, and shrimp.

Table 3. Aquatic organisms that feeding ground in Lake Siombak

Rainy Season	**Dry Season**	**Each Season**
Trichopodus pectoralis	*Ambassis buruensis*	*Mystus gulio*
Trichopodus trichopterus	*Anguilla bicolor*	*Megalops cyprinoides*
Channa striata	*Butis gymnopomus*	*Penaeus merguiensis*
Clarias bathracus	*Ophiocara porocephala*	*Parapenaeopsis coromandelica*
Monopterus albus	*Chanos chanos*	
Scylla olivacea	*Acentrogobius viridipunctatus*	
Scylla serrata	*Brachygobius xanthozonus*	
	Zenarchopterus buffonis	
	Lutjanus johnii	
	Valamugil engeli	
	Scatophagus argus	

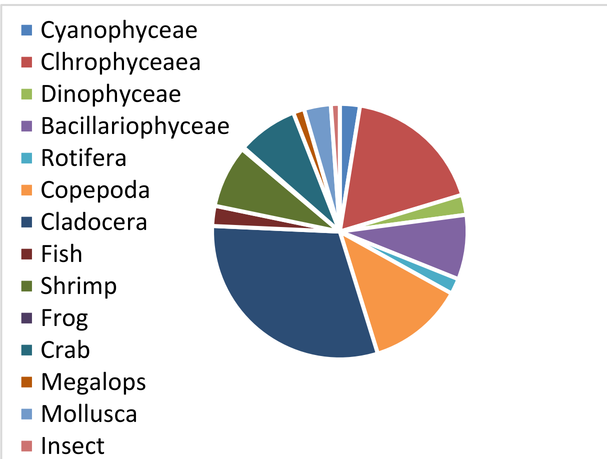


Figure 6. The percentage of the frequency of food groups that are eaten by fish and crustaceans in Lake Siombak.

4. Conclusion

From the results of this study, it can be concluded that Lake Siombak, as part of the Belawan River estuary, has an important role as a nursery area and feeding ground for fish, crustaceans, and even jellyfish found around the Belawan River estuary and its surroundings. There are at least nine families consisting of 6 fish families, 2 crustacean families, and 1 Cnidaria family that come to Lake Siombak. In addition, there are at least 22 species of adult fish that make Lake Siombak a feeding ground, which of course, "alternately" visit the lake according to the changing seasons. Therefore, it is important to maintain the sustainability of this lake to support the sustainability of fisheries productivity in the Belawan River estuary and its surroundings.

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Conflict of interest

This manuscript has no identified and possible conflicts of interest among authors

Data availability statement

All data included and used in the study is open and contains no confidential and ethically private information.

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AM contributed to designing the topic and research methods, data collection and analysis, and wrote the manuscript. **AP** contributed to data collection and analysis, wrote the manuscript. **RM** contributed to data analysis and wrote the manuscript.

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Ecological Study of Mangrove Crabs (*Scylla* spp.) on Jambu Beach, Dompu Regency: Diversity and Abundance in the Mangrove Ecosystem

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Abstract: This study aims to analyze the abundance and diversity of mangrove crabs (*Scylla spp.*) in the mangrove area of Jambu Beach, Pajo District, Dompu Regency, West Nusa Tenggara. The research was conducted from October to December 2024 using a quantitative descriptive survey method. Sampling was carried out purposively at three stations with different substrate types: mud, clay, and black mud. Specimens were captured using collapsible traps for eight hours with three replications. The identification results revealed three species of *Scylla spp.*, namely *S. serrata*, *S. paramamosain*, and *S. tranquebarica*. The total abundance ranged from 0.36 to 0.48 ind/m², with the highest found at Station 2 (0.48 ind/m²). The diversity index (H') ranged from 0.349–0.995, the evenness index (E) from 0.318–0.906, and the dominance index (D) from 0.037–0.089. The highest diversity (H' = 0.995) and evenness (E = 0.906) were recorded at Station 3, while the highest dominance occurred at Station 2 (D = 0.089). Statistical analysis using one-way ANOVA showed significant differences in abundance among stations (F = 24.818; p = 0.001). These results indicate that variations in substrate, salinity (30–32 ppt), temperature (28–29°C), and soil pH (7.1–7.3) influence the abundance and community structure of *Scylla* spp. in the mangrove ecosystem. The findings provide baseline data for the sustainable management of mangrove crab populations and conservation of coastal ecosystems in the Dompu region.

Keywords: Biodiversity index, species abundance, crustacean ecology, mangrove habitat, population structure, West Nusa Tenggara

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1. Introduction

Mangrove crabs (*Scylla* spp.) are fauna that inhabit coastal and shallow water ecosystems, particularly in areas dominated by mangrove forests (Gita, 2016). Mangrove forests provide various essential ecosystem services (Pambudi *et al.*, 2019), including the supply of nutrients such as organic matter, nitrate, and phosphate. The organic matter content plays a role in determining sediment characteristics, including pH, fertility levels, and the rate of litter decomposition (Puspitasari, 2014; Citra *et al.*, 2020).

The biological activities of mangrove crabs, such as burrowing and foraging on the substrate, influence sediment structure by enhancing oxygen and nutrient circulation, thereby supporting ecosystem fertility (Murniati *et al.*, 2016). In addition, microorganisms in the sediment also play a role in nutrient cycling and energy flow (Widyastuti, 2016).

Various studies have examined the ecological roles and abundance of *Scylla* spp. in several regions of Indonesia. For example, Pambudi *et al*., (2019) reported high abundance in the mangrove forests of Pasar Banggi, Rembang. Research conducted in the waters of North Lingga also showed high diversity and evenness values (Widyastuti, 2016). Apart from their ecological importance, *Scylla* spp. also have high economic value. Since the 1980s, this commodity has become one of the leading export products to various countries such as Singapore, Thailand, Taiwan, Hong Kong, China, as well as the United States and Europe (Dewi & Setiawina, 2013; Sulistiono *et al*., 2016).

Scylla spp. is classified under the class Crustacea, order Decapoda, family Portunidae, and consist of four main species found in Indonesian waters: *Scylla serrata*, *Scylla olivacea*, *Scylla tranquebarica*, and *Scylla paramamosain* (Gita, 2016; KKP, 2016). Their distribution varies, such as three species found along the northern and southern coasts of Java, four species in Papua, two in Asahan, North Sumatra, and in East Kalimantan (Pane & Suman, 2018; Aisyah *et al*., 2019).

However, research on *Scylla* spp. in Dompu Regency, West Nusa Tenggara, remains limited to date. Existing studies have primarily focused on mangrove vegetation rather than faunal biodiversity (Sentosa & Nastiti, 2012). The West Nusa Tenggara region has extensive mangrove forests, covering approximately 39.000 hectares, which serve as critical nursery grounds for various aquatic species, including mangrove crabs.

In recent years, these mangrove ecosystems have faced increasing pressures from land conversion, sedimentation, and coastal exploitation. Despite their ecological and economic importance—particularly as a source of livelihood for local communities, the scientific data on the abundance and diversity of *Scylla* spp. in this area are still lacking. Therefore, this study aims to examine the abundance, diversity, and community structure of *Scylla* spp. in the mangrove area of Jambu Beach, Pajo District, Dompu Regency. The findings are expected to provide essential baseline data to support mangrove conservation, sustainable management of coastal resources, and the development of local community-based fisheries in the Dompu region.

Therefore, this study aims to examine the abundance, diversity, and community structure of *Scylla* spp. in the mangrove area of Jambu Beach, Pajo District, Dompu Regency. The findings are expected to provide essential baseline data to support mangrove conservation, sustainable management of coastal resources, and the development of local community-based fisheries in the Dompu region.

2. Materials and Methods

2.1. Time and Location of Study

This research was conducted in the mangrove area of Jambu Beach, located in Pajo District, Dompu Regency, West Nusa Tenggara (Figure 1). The study was carried out from February to March 2025, encompassing the stages of preliminary observation, sample collection, and subsequent laboratory and statistical data analysis. Jambu Beach represents one of the main mangrove ecosystems in Dompu, characterized by extensive muddy and clay substrates that serve as suitable habitats for mangrove crabs (*Scylla* spp.). This spatial design allowed a comprehensive representation of environmental variation across different substrate types, ensuring that the collected data accurately reflected the ecological diversity of *Scylla* spp. in the mangrove ecosystem of Jambu Beach.

2.2. Tools and Materials

The tools used in this research included collapsible traps measuring 35 × 25 × 20 cm, knives, plastic buckets, raffia string, measuring tape, a GPS for recording station coordinates, a digital camera, and an identification guidebook for *Scylla* spp. The materials used included fresh fish bait, field data forms, and 70% alcohol for temporary fixation of specimens.

2.3. Population and Sample

The research population consisted of all individuals of *Scylla* spp. found in the mangrove forest area of Jambu Beach. The observed samples were *Scylla* spp. individuals caught within observation plots at three stations using collapsible traps, selected through purposive sampling.

2.4. Research Design and Data Collection

This study is quantitative descriptive research using a field survey approach, starting with environmental observation and brief interviews with officers from the local Marine and Fisheries Department. The research location was divided into three stations based on substrate characteristics: Station 1 with mud substrate, Station 2 with clay substrate, and Station 3 with black mud substrate. Each station was spaced 200 meters apart and consisted of three transects, each with two plots measuring 10 × 10 meters, which were used as sampling areas for *Scylla* spp (Figure 2A and Figure 2B).

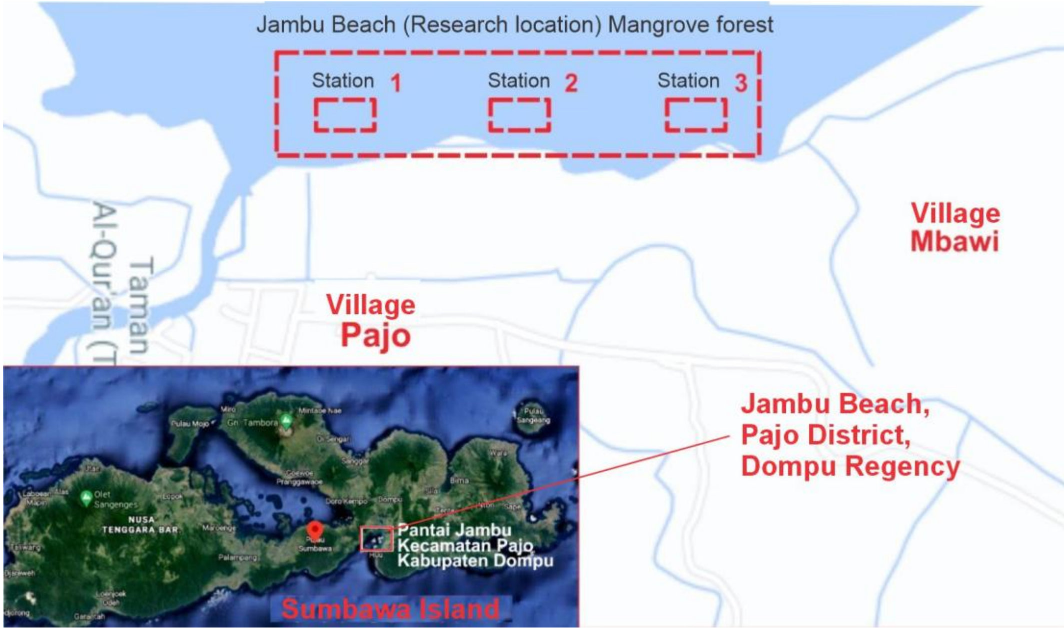

Figure 1. Map of the research location in the mangrove area of Jambu Beach, Pajo District, Dompu Regency (Google Maps). The red dashed boxes indicate the mangrove forest area where the three observation stations were established.

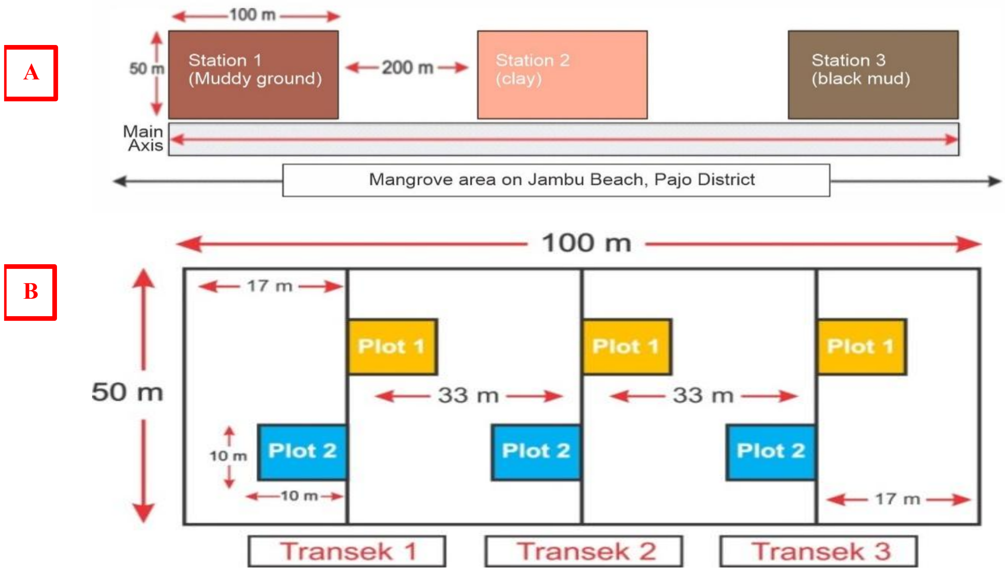

Figure 2. (A). Location of Stations 1–3. (B) Layout of Transects 1–3, each consisting of two plots.

2.5. Capture and Identification of *Scylla* spp.

At each plot, six traps were set up for eight hours of observation (08:00–16:00 Central Indonesia Time) with three repetitions on different days. Captured *Scylla* spp. were collected and morphologically identified based on carapace tooth shape and claws, referring to Sulistiono *et al.*, (2016) and Carpenter *et al.*, (1998) in Murniati *et al.*, (2016).

2.6. Observed Parameters

The observed parameters in this study included the number of individuals per species, the identified *Scylla* spp. species, their distribution and abundance at each station, and environmental characteristics such as soil pH, temperature, salinity, and substrate composition. Environmental parameters were measured directly at each sampling site using standardized field instruments: a portable thermometer for temperature (°C), a digital pH meter for soil acidity, and a hand refractometer for salinity (ppt).

Substrate samples were collected from each station at a depth of 0–10 cm and analyzed for texture composition (sand, silt, and clay fractions) using the pipette method (Hadiyanto *et al.*, 2018). These data were used to describe the environmental conditions influencing the distribution and abundance of *Scylla* spp. in the mangrove ecosystem.

Table 1. Observed Parameters

No	Observed Parameter	Description
1	Number of individuals per species	Total count of *Scylla* spp. individuals captured at each station
2	Species of *Scylla* spp.	Morphological identification to determine species
3	Distribution and abundance per station	Determination of the spread and relative number of individuals at each station
4	Environmental parameters	Measurement of temperature (°C), soil pH, and salinity (ppt) using thermometer, pH meter, and refractometer
5	Substrate composition	Analysis of sand, silt, and clay fractions using the pipette method

2.7. Data Analysis

Captured and identified *Scylla* spp. were analyzed to measure abundance differences between stations using one-way ANOVA. Data were processed using SPSS version 22. According to Ghozali (2015), ANOVA is used to compare the means of several populations. If the test result shows a significant p-value less than 0.05 ($\alpha < 0.05$), it indicates a significant difference in means; otherwise (p-value > 0.05), there is no significant difference (Laila et al., 2020). Following ANOVA, data were further analyzed by calculating the diversity index, dominance index, and density index. These data were presented descriptively to provide a comprehensive overview of the ecosystem conditions and *Scylla* spp. abundance at the study site.

2.8. Abundance of *Scylla* spp.

The abundance of *Scylla* spp. was calculated using the formula (Siringoringo *et al.*, 2017):

$$N = \frac{\sum \mathrm{ni}}{A}$$

Where:

N = abundance of mangrove crabs of species *i* (individuals/m²)

∑ ni = total number of individuals of species *i*

A = area of observation plot (m²)

2.9. Diversity Index

The *Scylla* spp. data were then analyzed using the Shannon-Wiener diversity index (H′) as follows (Santosa *et al.*, 2008):

$$H' = -\sum P_i \ln (P_i), \text{ where}$$

$$Pi = \frac{ni}{N}$$

where:
H'= Shannon-Wiener diversity index
ni = number of individuals of species *i*
N = total number of individuals of all species
Criteria for the Shannon–Wiener diversity index (H') are as follows:

H' < 1	:	Low diversity
1 ≤ H' ≤ 3	:	Moderate diversity
H' > 3	:	High diversity

2.10. Evenness Index

Evenness was calculated using the following formula (Syahrera *et al.*, 2016):

$$E = \frac{H'}{ln(S)}$$

Where:
E= Evenness index
H= Shannon-Wiener diversity index
S = Number of species

2.11. Dominance Index

Dominance of particular species was determined using the dominance index formula (Fachrul, 2012):

$$D = \sum_{i=1}^{s} \left(\frac{ni}{N}\right)^2$$

Where:
D = Dominance index
ni = number of individuals of species *i*
N = total number of individuals

Dominance index values range from 0–1. The higher the index value, the greater the tendency for dominance by a particular species.

3. Results

The results of this study describe the species composition, abundance, and ecological structure of *Scylla* spp. in the mangrove area of Jambu Beach. Three species were successfully identified: *Scylla* serrata, *Scylla* paramamosain, and *Scylla* tranquebarica. Among these, S. serrata dominated the total catch across all sampling stations, while S. tranquebarica was found in the smallest number. Variations in individual counts, abundance, and ecological indices such as diversity (H'), evenness (E), and dominance (D) were observed among stations, reflecting differences in habitat characteristics, substrate types, and environmental parameters. Detailed results are presented in the following tables.

Table 2. Number of Individuals and Species of *Scylla* spp. per Station

Station	Species	Number of Individuals
Station 1	*Scylla serrata*	12
	Scylla paramamosain	4
	Scylla tranquebarica	2
Station 2	*Scylla serrata*	15
	Scylla paramamosain	6
	Scylla tranquebarica	3
Station 3	*Scylla serrata*	10
	Scylla paramamosain	7
	Scylla tranquebarica	5

The distribution of *Scylla spp.* abundance at each station showed a noticeable difference, with Station 2 having the highest number of individuals. Abundance values were calculated based on the total number of individuals found divided by the sampling area at each station (Table 3). The substrate conditions were dominated by fine mud to sandy mud, which is an ideal habitat for mangrove crabs (Table 4).

Table 3. Abundance Distribution of *Scylla* spp.

Station	Total Number of Individuals	Abundance (Ind/m²)
Station 1	18	0,36
Station 2	24	0,48
Station 3	22	0,44

Table 4. Substrate Conditions and General Environment

Station	Substrate Type	Temperature (°C)	Soil pH	Salinity (ppt)
1	Fine mud	28	7,1	30
2	Sandy mud	29	7,3	32
3	Predominantly mud	28,5	7,2	31

3.1. Ecological Index and Statistical Analysis of *Scylla* spp. Abundance

The calculation results of the ecological indices of *Scylla* spp. (*Scylla* serrata, *Scylla* paramamosain, and *Scylla* tranquebarica) in the mangrove forest area of Jambu Beach shows variations among the three observation stations. The values of the diversity index (H'), evenness (E), and dominance (D) presented in Table 5 illustrate the differences in the community structure of *Scylla* spp. at each location.

The highest diversity index (H') was found at Station 3 (0.995), followed by Station 1 (0.802), and the lowest at Station 2 (0.349). According to the Shannon-Wiener criteria (Baliton *et al.*, 2020), all stations still fall into the low diversity category (H' < 1), although there are value variations between stations. The evenness index (E) also indicates that Station 3 has the most even distribution of individuals among species (E = 0.906), while Station 2 shows the most uneven distribution (E = 0.318). This indicates that at Station 2, there is a more dominant species compared to the others. The highest dominance index (D) was found at Station 2 (0.089), indicating a relatively strong dominance of one species, while Station 3 had the lowest dominance (0.037). Thus, Station 3 is considered to have a more balanced community structure compared to the other two stations.

3.2. Variation in *Scylla* spp. Abundance Across Stations

To determine whether the differences in *Scylla* spp. The abundance among the stations is statistically significant, an ANOVA test was conducted, and the results are presented in Table 6. The ANOVA test showed a significance value of 0.001 ($p < 0.05$), which means that there are significant differences in *Scylla* spp. abundance among the observation stations. The F-value of 24.818 also indicates a real variation that did not occur by chance. Overall, these results suggest that environmental factors and habitat conditions at each station most likely influence the community structure and abundance of *Scylla* spp. Station 3, which has the highest diversity and evenness values and the lowest dominance, can be said to have more favorable habitat conditions for a more even distribution of the three observed mangrove crab species.

Table 5. Diversity Index (H'), Evenness (E), and Dominance (D) of *Scylla* spp.

Station	(H')	(E)	(D)
1	0,802	0,73	0,054
2	0,349	0,318	0,089
3	0,995	0,906	0,037

Table 6. ANOVA Test Analysis of *Scylla* spp. Abundance

	Sum of Squares	*df*	*Mean Square*	*F*	*Sig.*
Between Groups	60,667	2	30,333	24,818	.001
Within Groups	7,333	6	1,222		
Total	68,000	8			

4. Discussion

This study revealed the presence of three species of mangrove crabs (*Scylla* spp.) found in the mangrove area of Jambu Beach, namely *Scylla* serrata, *Scylla* paramamosain, and *Scylla* tranquebarica (Figure 3). The identification results showed that *Scylla* serrata was the most dominant species at all observation stations. This aligns with the ecological characteristics of S. serrata, which is more tolerant of various environmental conditions, particularly the muddy substrate that dominates the research area. This type of substrate provides protection and facilitates feeding and hiding activities, as reported in studies by Avianto et al. (2013) and the Ministry of Marine Affairs and Fisheries (KKP, 2016).

The highest abundance was recorded at Station 2 with a value of 0.48 ind/m², followed by Station 3 (0.44 ind/m²) and Station 1 (0.36 ind/m²). This difference is most likely influenced by environmental factors such as substrate type and physical water parameters (temperature, soil pH, and salinity). Station 2, which has a sandy-mud substrate and the highest salinity (32 ppt), may provide more optimal conditions for crab growth and activity, particularly in terms of substrate oxygenation and the availability of detritus-based food (Awuku-Sowah *et al.*, 2022). A similar relationship between substrate type, salinity, and the abundance of *Scylla* spp. has also been reported along the eastern coast of North Sumatra (Onrizal & Kusmana, 2008) and in the mangrove ecosystems of Sarawak, Malaysia (Ikhwanuddin *et al.*, 2011), showing that semi-sandy mud provides ideal conditions for higher survival rates and feeding efficiency in S. serrata populations.

Figure 3. Identified *Scylla* species. (A). *Scylla* tranquebarica. (B). *Scylla* serrata. (C). *Scylla* paramamosain.

Although the highest abundance was recorded at Station 2, the highest diversity index (H') was found at Station 3 (0.995), indicating a more balanced species composition. The evenness index (E) also supports this finding, with Station 3 showing the most even distribution of individuals among species (E = 0.906). In contrast, Station 2 exhibited the lowest H' value (0.349) and the lowest E value (0.318), indicating a strong dominance by a single species (in this case, S. serrata) and a lower presence of other species. This is further supported by the highest dominance index (D) at Station 2 (0.089), indicating an imbalanced community structure. These diversity patterns are consistent with findings from India (Raj *et al.*, 2025) and the Bay of Bengal, Bangladesh (Habib *et al.*, 2023), which demonstrated that habitat heterogeneity and substrate variation directly influence the diversity and dominance levels of *Scylla* spp.

The ANOVA test results provide strong evidence that the differences in abundance among stations are statistically significant ($p < 0.05$). This indicates that environmental factors play an important role in shaping the community structure of mangrove crabs. With an F-value of 24.818 and a significance level of 0.001, it can be concluded that the variation in abundance did not occur randomly but was influenced by specific ecological conditions at each station. Comparable results were also obtained by Gita (2016) and Habib *et al.*, (2023), who found that environmental heterogeneity significantly affects the spatial distribution of *Scylla* spp. across various mangrove zones.

Ecologically, the high diversity and evenness observed at Station 3 indicate a relatively stable environment capable of supporting multiple species. This is important for maintaining the balance of the mangrove ecosystem, as mangrove crabs play a crucial role in the decomposition of organic matter, nutrient cycling, and strengthening of substrate structure through their burrowing activities. These findings emphasize the importance of conserving mangrove habitats and sustainably managing coastal environments to maintain the existence and balance of *Scylla* spp. populations, particularly in the context of climate change and increasing human pressures in coastal areas. This aligns with the global perspective that mangrove biodiversity contributes significantly to coastal ecosystem resilience and carbon sequestration (Lee *et al.*, 2014; Raynaldo *et al.*, 2024; Collins *et al.*, 2021), highlighting the need for integrated management and conservation of mangrove-associated fauna.

5. Conclusion

This study revealed the presence of three species of mangrove crabs (*Scylla* spp.) in the mangrove area of Jambu Beach, Pajo District, Dompu Regency, namely *Scylla* serrata, *Scylla* paramamosain, and *Scylla* tranquebarica, with S. serrata being the most dominant species across all stations. The highest abundance was found at Station 2, while the highest diversity and evenness indices were recorded at Station

3. These findings indicate that variations in environmental conditions, such as substrate type, temperature, soil pH, and salinity, influence the distribution and community structure of *Scylla* spp. in the study area. The results suggest that the mangrove ecosystem at Jambu Beach provides a suitable habitat for the growth and survival of mangrove crabs. Further studies covering broader temporal and spatial scales are recommended to better understand population dynamics and habitat preferences of *Scylla* species in mangrove ecosystems.

Data Availability Statement

The data included and used in this study is not confidential and is available upon request.

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Conflict of Interest

The authors declare no conflict of interest in the conduct of this study.

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Author Contribution

Nikman Azmin played a role in designing the research, determining the sampling locations and methods, and conducting field data collection at the three research stations. Nikman was also responsible for the identification of *Scylla* spp. species, processing data on diversity and abundance, and preparing the results and discussion sections. **M. Ekahidayatullah** contributed to developing the research concept, performing statistical analyses (including ANOVA tests), interpreting ecological aspects of environmental parameters, and integrating the research findings into the context of coastal resource management. In addition, he wrote the introduction, abstract, and conclusion sections, carried out overall manuscript revision, and served as the corresponding author during the publication process.

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Bibliometric Trends in Diatom Research: Emphasis on Lakes and Oxbow Lakes Ecosystems

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Abstract: Diatoms are unicellular microalgae that play a critical role as bioindicators of freshwater environmental conditions. This paper delivers a literature review and bibliometric analysis of diatom composition and distribution in lakes, with a particular focus on oxbow lakes. We compiled bibliometric data from Scopus and analyzed them using R with the Bibliometrix package to characterize publication trends, thematic emphases, and scholarly influence. The analysis reveals a persistent growth in diatom-related research over the last two decades, driven by themes such as climate change, habitat degradation, and environmental monitoring. The Journal of Paleolimnology emerges as a leading venue, with its impact shaped by key contributors who have significantly advanced publication volume and scientific influence in the field. Despite the ecological importance of oxbow lakes, their representation in the diatom literature remains limited, suggesting notable gaps and opportunities for future investigation. The findings underscore the value of interdisciplinary approaches to advance understanding and inform the conservation and sustainable management of freshwater ecosystems.

Keywords: Diatom, Bioindicator, Oxbow Lake, Bibliometric, Climate Change

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1. Introduction

Diatoms are a category of microalgae characterized by varied silica compositions that significantly contribute to aquatic ecosystems and have been extensively employed as bioindicators for evaluating water quality and conducting environmental monitoring. Diatom ecological sensitivity, swift reactions to environmental alterations, and considerable species variety render them exceptionally suitable for comprehending historical and contemporary ecosystem dynamics (Smol &

Stoermer, 2010). Despite significant advancements in global research on diatom applications, a thorough bibliometric analysis of diatom studies, particularly in distinctive aquatic systems such as oxbow lakes, remains scarce, particularly concerning freshwater ecosystems in Indonesia.

Oxbow lakes are U-shaped lentic water bodies formed when a meandering river becomes separated from its main channel through natural processes or anthropogenic activities (Delhomme et al., 2013; Saha et al., 2022). These lakes play a significant role in regulating alluvial processes within flood plains (Constantine et al., 2010). Due to their distinct hydrological characteristics, oxbow lakes are dynamic, biologically diverse, yet highly fragile ecosystems. In addition to supporting diverse micro-floral and faunal communities in river basins and major fluvial systems, these lake types also serve as vital habitats for feeding, breeding, and providing refuge during extreme flood events, emphasizing their importance for conservation (Dembowska & Kubiak-Wojcicka, 2017; Naus & Reid Adams, 2018).

The present study applies Bibliometric, an R-based package for comprehensive bibliometric analysis, to delineate and evaluate global and national trends in diatom research, with a particular emphasis on its application in oxbow lakes. Bibliometric analysis is crucial for developing a comprehensive understanding of the current state and future directions of research within a specific scientific field (Khudzari et al., 2018). This study enables the application of diverse mathematical, statistical, and graphical techniques to scrutinize scholarly papers comprehensively (Han et al., 2020). Through this approach, we can examine research trends, the contributions of countries, journals, and institutions, as well as the flow of scientific knowledge within a specific topic area (Bezak et al., 2021; Ubando et al., 2021). Furthermore, co-occurrence analysis of keywords enables the identification of historical trends, contemporary themes, and emerging research frontiers (Ilmasari et al., 2022).

Previous studies have applied bibliometric approaches to diatom-related topics in various scientific contexts. For instance, Sahabudin et al. (2024) conducted a bibliometric analysis of diatoms to elucidate research trends related to fatty acids and their potential for biofuel production. Wu et al. (2024) employed bibliometric network analysis to gain insights into research modelling in the aquatic domain from 1962 to 2022. Falah et al. (2024) explored the potential of environmental DNA using a paleolimnological technique via bibliometric mapping.

The primary objective of this study is to identify and analyze current research patterns, future trends, and potential research gaps in diatom studies, specifically those focused on biomonitoring in lake ecosystems. The search process transitioned from general exploration to a more specific investigation of research topics. Oxbow Lake was not a popular research theme, with diatoms as the primary topic; we compared "lake" and "oxbow lake" to analyze the opportunities and threats for improving this research. Consequently, the relevant keywords for each topic were incorporated into the search string. We also analyzed the methodological and contextual challenges of studying oxbow lakes via diatoms, highlighting the emerging opportunities for interdisciplinary research and community engagement.

2. Materials and Methods

2.1. Data Collection

Bibliometric data were collected from the Scopus database on April 22, 2025. Scopus was selected as the data source to achieve the study’s objective due to its extensive coverage and analytical capabilities. The Scopus database also integrates all MEDLINE journals and supports detailed citation analysis, enabling accurate mapping of scholarly influence and collaboration networks (Falagas et al., 2008; Kulkarni et al., 2009). Moreover, Scopus provides multiple operational features that facilitate bibliometric evaluations, including metadata on journal titles, document types, publication years, authors and affiliations, citation counts, and h-index metrics (Hirsch, 2005; Agarwal et al., 2016). These functions make Scopus particularly suitable for conducting comprehensive and reproducible bibliometric studies.

This study's central focus is research articles concerning diatoms as bioindicators in lake ecosystems. A comprehensive bibliometric analysis was performed using bibliographic data related to diatom research retrieved from the Scopus database. The search strategy compared the keywords "diatom" AND "lake" AND "bioindicator" AND "climate change" for the years 2000 to 2025 with the keywords "diatom" AND "oxbow lake" AND "bioindicator" AND "climate change" from 2001 to 2021. Only peer-reviewed journal articles, conference papers, and English-language review articles were included. The data were exported in BibTeX format, compatible with Bibliometrix, an R package for bibliometric analysis (Aria & Cuccurullo, 2017). The search for the "diatom" AND "lake" AND "bioindicator" AND "climate change" keyword yielded 36 articles, while the "diatom" AND "oxbow lake" AND "bioindicator" AND "climate change" keyword produced 24 articles. However, when additional fields were included in the search scope, the results for "oxbow lake" decreased to a single article, indicating that diatom research within oxbow lake ecosystems remains underrepresented in the scientific literature.

2.2. Data Analysis

The data processing and analysis were conducted using RStudio v2024.12.1+563. The bibliometric analysis was performed using the bibliometrix package in R. The installation process began by typing "install.packages('bibliometrix')" in the console tab to install the bibliometric package. During the installation, a CRAN mirror was selected to ensure a stable and secure connection for downloading. In this study, the CRAN mirror "Indonesia (Banda Aceh) [https]" was chosen because it provided a reliable and regionally optimized source. After the installation was completed, the package was loaded by typing "library(bibliometrix)" and press enter. Subsequently, the command "biblioshiny()" was executed in the console tab to launch biblioshiny, the web-based interface used for conducting the bibliometric analysis (Machmud et al., 2023).

3. Results and Discussion

3.1. Main Information

A bibliometric analysis of the composition and distribution of diatoms in lakes as freshwater bioindicators was conducted using a single screening. The initial literature screening used the keywords "diatom," "oxbow lake," "bioindicator," and "climate change" for 2001 to 2021 and identified 24 documents published across 19 sources. The annual growth rate of publications was 0% (stable output over the period). The documents have a mean age of 12.8 years and a mean of 23 citations per article (552 total), equivalent to about 1.8 citations per article per year. There are 364 Keywords Plus and 106 author-provided keywords, reflecting diverse research topics. In total, 96 authors contributed; only two documents were single-authored and an average of 4.25 co-authors per document, reflecting a collaborative research environment. International collaboration is evident in 20.83% of the publications. Most documents are journal articles (23), with only one conference paper (Table 1).

Table 1. Main Information using the keywords "diatom," "oxbow lake," "bioindicator," and "climate change".

Main Information About Data	
Timespan	2001 to 2021
Sources (Journal, Books, etc)	19
Documents	24
Annual Growth Rate %	0
Document Average Age	12.8
Average citations per doc	23
References	0
Document Contents	
Keywords Plus (ID)	364
Author's Keywords (DE)	106
Authors	
Authors	96
Authors of single-authored	2
Authors Collaboration	
Single-authored docs	2
Co-Authors per Doc	4.25
International co-authorship %	20.83
Document Types	
Article	23
Conference paper	1

A bibliometric analysis from 2000 to 2025 identified 36 documents published across 21 sources. The annual growth rate remains 0%, while the average document age is 9.03 years, reflecting more recent publications. The average citations per document is 19.39, slightly lower than the previous dataset.

Table 2. Main Information using the keywords "diatom," "lake," "bioindicator," and "climate change".

Main Information About Data	
Timespan	2000 to 2025
Sources (Journal, Books, etc)	21
Documents	36
Annual Growth Rate %	0
Document Average Age	9.03
Average citations per doc	19.39
References	0
Document Contents	
Keywords Plus (ID)	576
Author's Keywords (DE)	150
Authors	
Authors	175
Authors of single-authored	0
Authors Collaboration	
Single-authored	0
Co-Authors per Doc	5.11
International co-authorship %	44.44
Document Types	
Article	34
Conference paper	2

This dataset features 576 Keywords Plus terms and 150 author-provided keywords, indicating an even broader thematic scope. In total, 175 authors contributed, with no single-authored documents and an average of 5.11 co-authors per document, highlighting increased collaboration. International co-authorship rises to 44.44%, demonstrating stronger global research cooperation. The document types include 34 articles and 2 reviews, indicating a slight diversifying in publication formats (Table 2).

Overall, both tables illustrate the evolution of diatom research in lakes, with increasing collaboration, expanding thematic diversity, and a growing trend toward international partnerships in recent years. These patterns reflect the research's dynamic and interdisciplinary nature on diatoms as bioindicators in freshwater ecosystems.

3.2. Classification of Leading Journals, Authors, Affiliations, Countries, and Documents

3.2.1. Leading Journals

The analysis of most relevant sources reveals a substantial disparity in scholarly focus between lake and oxbow lake. Research on lake ecosystems is considerably more prevalent, with the Journal of Paleolimnology emerging as the dominant outlet publishing nine articles. Other articles with notable representation in lake studies include Holocene (three articles), and Water (Switzerland), Science of The Total Environment, Journal of Great Lakes Research and Water, Air, and Soil Pollution (two articles each). Meanwhile, research on diatoms in oxbow lake environments is significantly less represented. While the Journal of Paleolimnology still leads the oxbow lake category with four articles, other contributors like Hydrobiologia and Quaternary science reviews published only two articles. The remaining oxbow lake publications are scattered, often represented by only one article, highlighting the limited research output and fragmented scholarly attention dedicated to these unique aquatic ecosystems (Figure 1).

Source Local Impact (H-index) between studies on lake and Oxbow Lake revealing a distinct asymmetry in research visibility and influence. Journal of Paleolimnology shows the highest local impact across all sources with H-index of 9 for lake and 4 for oxbow lake. Other articles with moderate impact in lake studies include Holocene (H=3), Science of the total environment, water (Switzerland), Journal of Great Lakes Research, and Diatom Research (each with H = 2). In contrast, studies focusing on oxbow lake environments display lower and more fragmented research impact. The highest H-index for oxbow lake articles (H=4) is also attributed to the Journal of Paleolimnology, followed by Quaternary Science Reviews and Hydrobiologia (H=2). Most other sources, including Geomicrobiology Journal, Enviromental Science and Pollution Research, and Canadian water resources journal, record only minimal impact (H=1). This limited citation performance suggests that studies in oxbow lake ecosystems are still in their development stage, characterized by sparse publication frequency and lower research visibility (Figure 2).

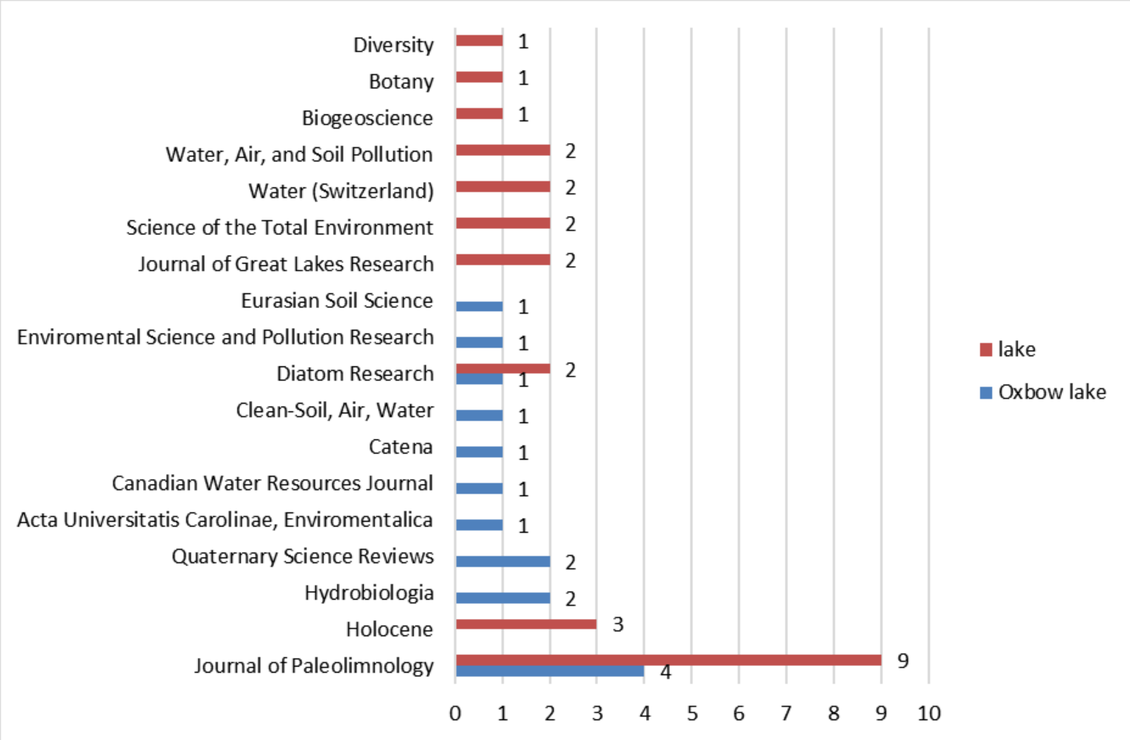

Figure 1. Most Relevant Sources between lake and oxbow lake

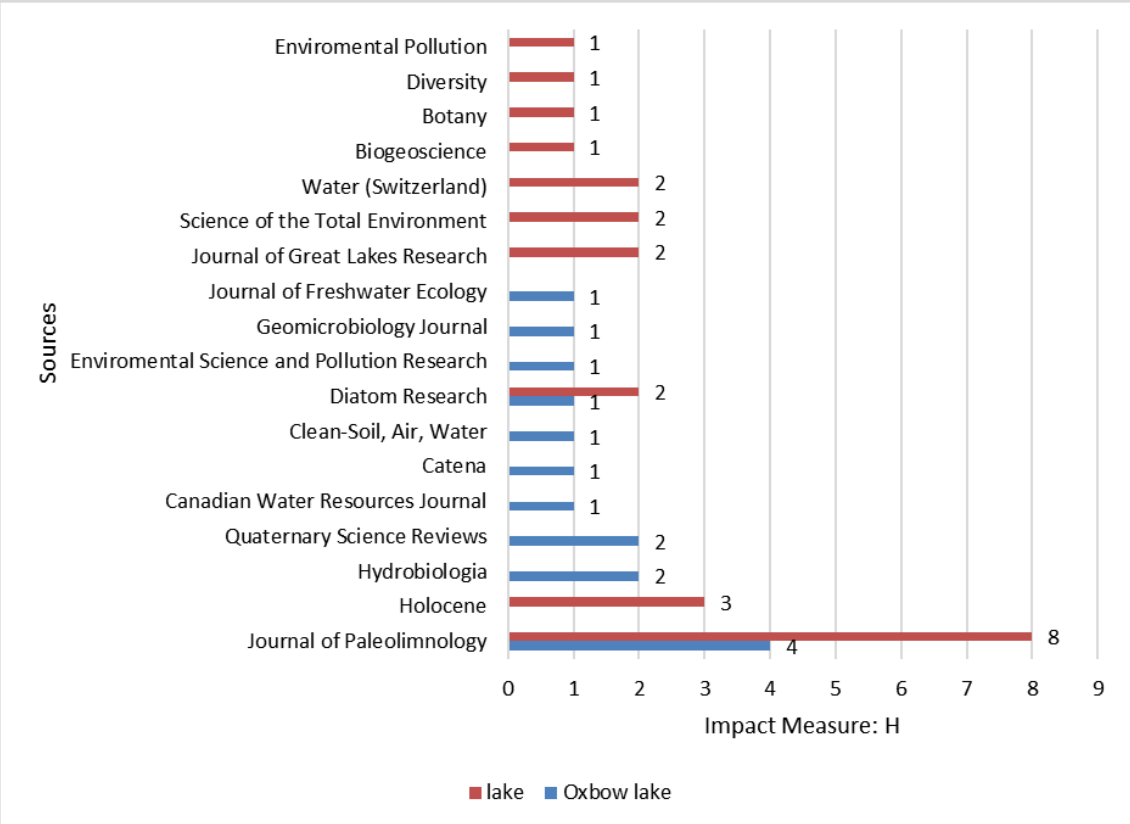

Figure 2. Source Local Impact between lake and oxbow lake

3.2.2. Authors

The production of articles on diatoms and oxbow lakes over time included 10 authors. Hall Roland I and Wolfe Brent B have a relatively higher number of publications than other authors, as indicated by the larger circle sizes around 2010. In addition, Dembowska Ewa A also demonstrated notable publication activity around 2018. Authors such as Espinosa Marcela A, Fayó Rocío, and Pan Jerónimo appear to have become active in publishing scientific works between 2018 and 2020, with relatively balanced productivity. Meanwhile, several other authors, including Abonyi András, Achimo Mussa, Afonso María dos Santos, and Armitage Derek, are recorded as having only one publication during earlier periods, approximately between 2004 and 2014, with lower citation counts (Table 3).

Table 3. Top Author Production Over Time for Diatom and Oxbow Lake

Author	Year	Freq	TC	TCpY
ABONYI A	2010	1	43	2.688
ACHIMO M	2015	1	27	2.455
AFONSO MDS	2004	1	54	2.455
ARMITAGE D	2010	1	16	1
DEMBOWSKA EA	2015	2	37	3.364
ESPINOSA MA	2018	1	18	2.25
ESPINOSA MA	2020	1	5	0.833
FAYÓ R	2018	1	18	2.25
FAYÓ R	2020	1	5	0.833
HALL RI	2010	2	65	4.063
PAN J	2018	1	18	2.25
PAN J	2020	1	5	0.833
WOLFE BB	2010	2	65	4.063

The results of the bibliometric analysis showed that the scientific production of authors focusing on the research theme of diatoms and lakes over time involved a total of 10 authors. As shown in Table 4, Reavie Euan D and Smol John P are two authors with more extended periods of productivity, each with more articles than others, as indicated by the larger circle sizes. Their publication activities were particularly significant from 2017 to 2020. Meanwhile, authors such as Barinova Sophia, Gabychev Viktor, and Genkal Sergey display more recent article production, specifically for 2023. Other authors like Wang Rong, Ahlborn Marieke, and Alexson Elizabeth E were also active during specific periods. However, the number of articles and citation levels they achieved were smaller compared to the two primary authors (Table 4).

Table 4. Top Author Production Over Time for Diatom and Lake

Author	Year	Freq	TC	TCpY
AHLBORN M	2021	1	4	0.800
ALEXSON EE	2018	1	5	0.625
BARINOVA S	2023	2	14	4.667
GABYSHEV V	2023	2	14	4.667
GENKAL S	2023	2	14	4.667
REAVIE ED	2018	3	32	4.000
SCHWALB A	2010	1	22	1.375
SCHWALB A	2021	1	4	0.800
SGRO GV	2018	2	27	3.375
SMOL JP	2017	1	20	2.222
SMOL JP	2021	2	24	4.800
SMOL JP	2024	1	0	0
WANG R	2011	1	36	2.400
WANG R	2019	1	35	5.000

Figures 3 presents the distribution of the most relevant authors contributing between lake and oxbow lake. In lake studies, Reavie Euan D and Smol John P emerge as the most prolific authors, each contributing three articles. In contrast, research on diatoms in oxbow lake demonstrates a more evenly distributed but comparatively lower level of author productivity. Authors such as Dembowska Ewa A, Espinosa Marcela A, Fayó Rocío, Hall Roland I, Pan Jerónimo, and Wolfe Brent B. Each authors contribute two articles, reflecting emerging but still limited scholarly engagement in this subfield. The absence of highly prolific authors and the presence of smaller publication counts suggest that oxbow lake studies are still developing as a distinct research niche, likely constrained by the limited availability of long-term datasets and region-specific investigations.

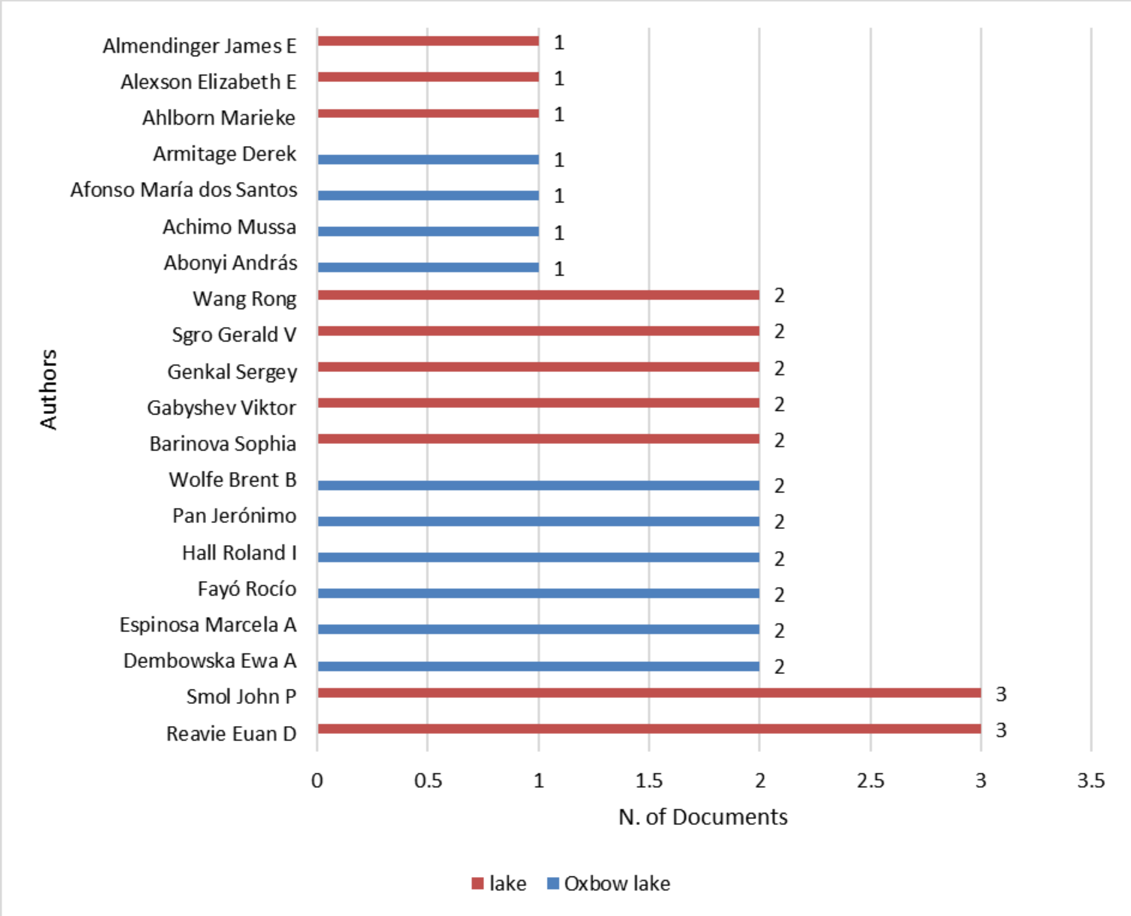

Figure 3. Most Relevant Authors between lake and oxbow lake

The results presented in Figure 4 indicate the local author impact (H-index) for researchers contributing to diatom studies in lake and oxbow lake ecosystems. The pattern reveals that lake exhibit a generally higher and more consistent impact compared to oxbow lake research. Reavie Euan D and Smol John P emerge as the most nfluential authors, both with an H-indeks of 3. Their sustained scholarly visibility reflects not only high publication productivity (as shown in Figure 4) but also strong citation performance, indicating that their works serve as key references in lacustrine diatom research. Several other authors like Barinova Sophia, Gabyshev Viktor, Genkal Sergey, Sgro Gerald V, and Wang Rong maintain moderate influence (H=2), suggesting active participation and recognition within the scientific cimmunity studying lake diatoms. The author impact for oxbow lake studies appears more evenly distributed but lower in magnitude. Dembowska Ewa A, Espinosa Marcela A, Fayó Rocío, Hall Roland I, Pan Jerónimo, and Wolfe Brent B record an H-index of 2, indicating moderate local recognition but limited citations accumulation compared to their counterparts working on lake systems (Figure 4).

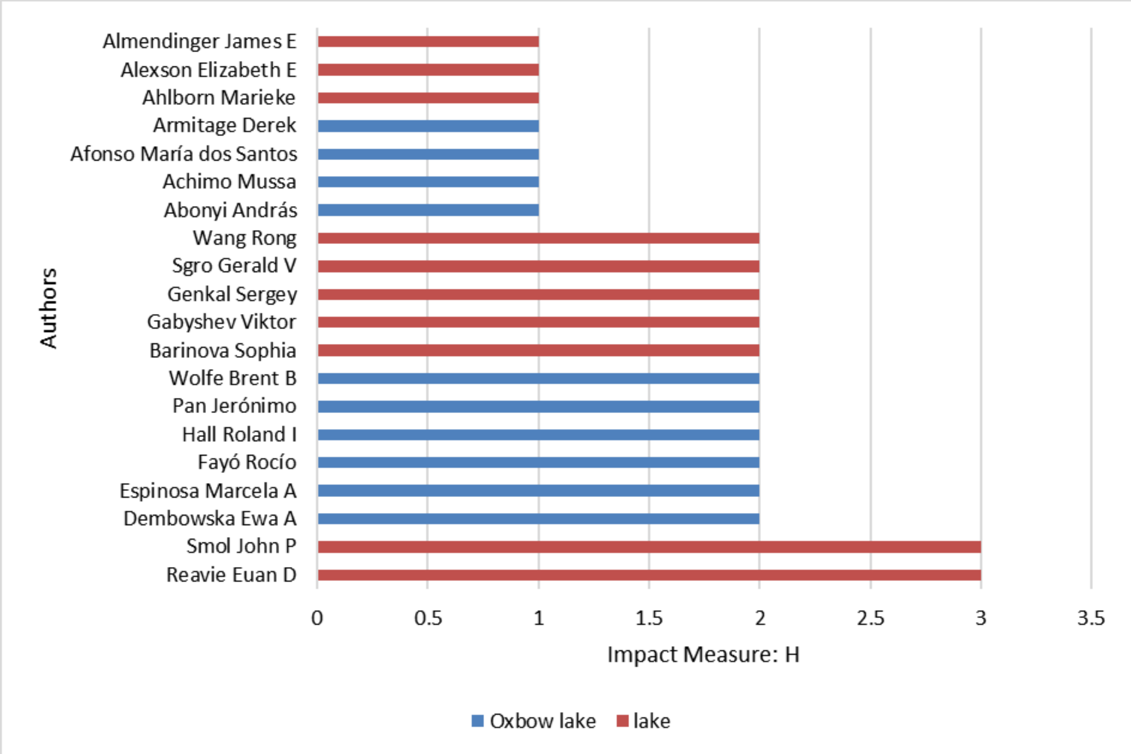

Figure 4. Author Local Impact between lake and oxbow lake

3.2.3. Affiliations

Figure 5 shows a comparison of institutions most relevant to lake and oxbow lake research. The findings reveal a distinct pattern in the distribution of research outputs across various institutions. General lake research seems to be more widespread, with several institutions, including the University of Minnesota Duluth and Queen's University, producing the highest number of outputs (n=3) among a variety of affiliations. Most other institutions involved in lake research have lower but steady levels of contributions. In contrast, oxbow lake research is more concentrated at a few key institutions. Stockholm University stands out as the top institution, with four research outputs. The University of Waterloo and Universidad de Buenos Aires follow, each contributing three outputs. This pattern indicates that while lake studies attract broader participation from various institutions, oxbow lake research relies primarily on a smaller group of specialised centres that are more active (Figure 5).

3.2.4. Co-occurrence Network

The network visualization reveals two distinct yet interconnected thematic clusters (Figure 6). The red cluster focuses on diatoms and related bioindicator topics, with large nodes such as diatom and Bacillariophyta indicating a high concentration of research activity around diatoms as indicators of aquatic health. The size and proximity of these nodes suggest strong research intensity and a central role for diatoms in assessing lake ecosystems. The blue-green cluster centers on climate change and freshwater ecosystem variables, including lake, lakes, water quality, and environmental monitoring. This cluster displays a dense network of connections among climate-related terms and hydrological factors, reflecting broad interdisciplinary work linking climate dynamics to lake ecology. Connections between the clusters show ongoing integration between climate and environment-based research and diatom bioindication. Overall, the visualization demonstrates a growing emphasis on diatoms as primary bioindicators within lake studies while maintaining significant attention to environmental monitoring, climate change, and comprehensive ecological assessment

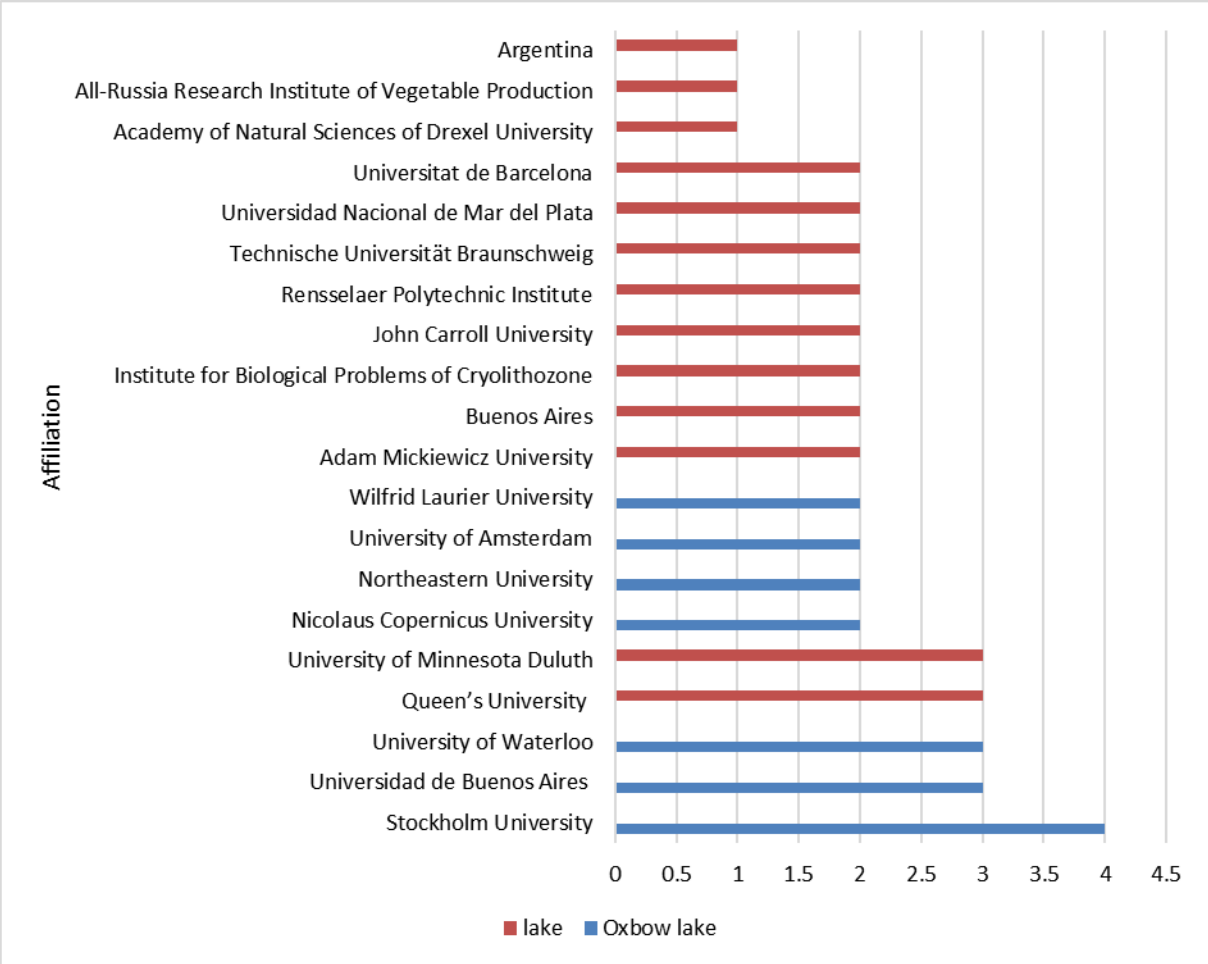

Figure 5. Most Relevant Affiliations between lake and oxbow lake

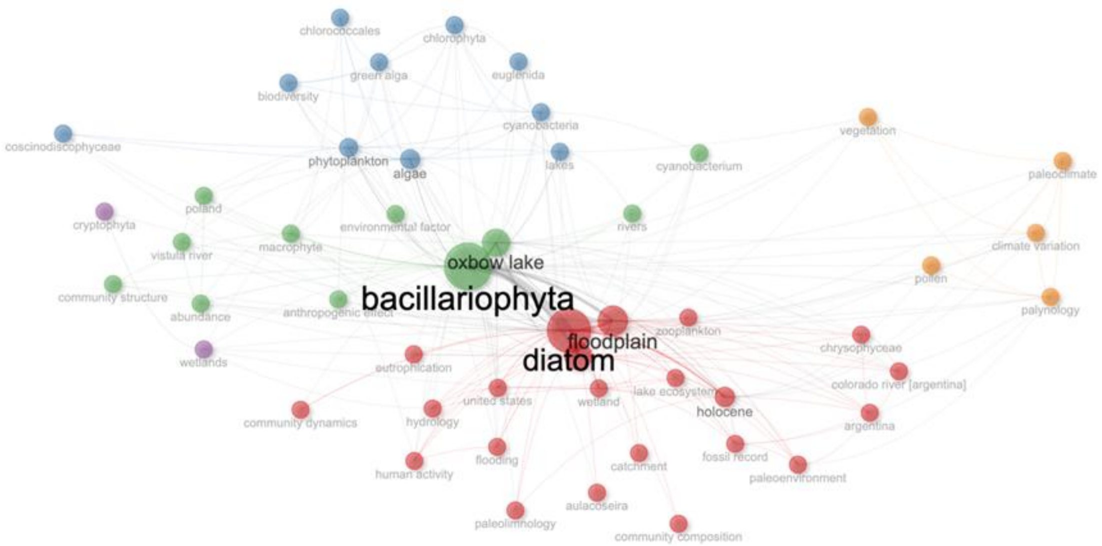

Figure 6. Co-occurrence Network for diatom and oxbow lake

The literature network visualization reveals two distinct thematic clusters (Figure 7). The blue cluster is centered on the concept of climate change and is closely associated with freshwater ecosystem variables, such as lakes, lake water, water quality, environmental monitoring, and related environmental factors. This cluster displays relatively uniform node sizes, indicating a broad thematic interconnection and varied depth of focus across those topics. In contrast, the red cluster focuses on bioindicator concepts, with pronounced attention on diatom indicators and related terms, including Bacillariophyta, paleoenvironments, global change, and aspects of paleoecology. The larger node sizes in the red cluster suggest higher research intensity on diatoms as bioindicators for assessing the health of aquatic environments. The visualization also highlights substantial interconnectivity between clusters, especially along research pathways linking climate variables and aquatic biogeochemistry with bioindicator concepts. This pattern demonstrates that research in this domain remains strongly interdisciplinary, merging climate dynamics, water quality assessment, and biotic community responses. Overall, the network structure points to a growing research emphasis on diatoms as primary bioindicators within lake studies, while also confirming the persistent relevance of environmental monitoring, climate change, and integrated ecological assessments. These findings share consistency with existing literature, emphasizing the increasingly central role of diatoms for evaluating the ecological effects of climate change on freshwater ecosystems and the necessity for synthesizing chemical, physical, and biological parameters in comprehensive environmental evaluations.

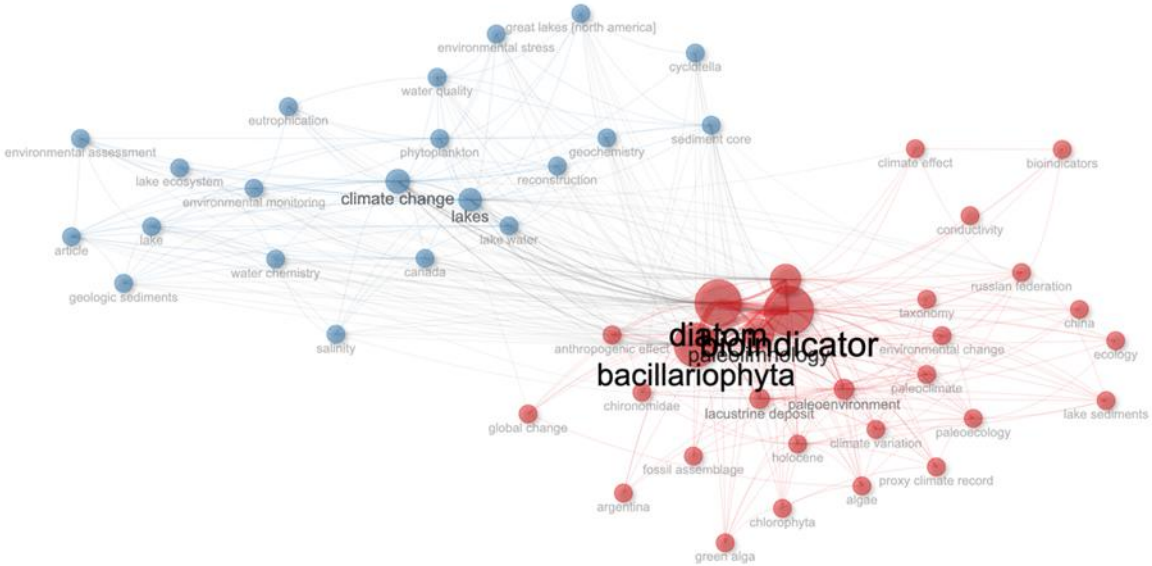

Figure 7. Co-occurance Network for diatom and lake

The analysis presented in Figure 8 demonstrates that research on lake and oxbow lake is highly concentrated within a select group of countries. Canada stands out as the most frequently cited with registering 119 citations. United States and chine surpassing both 108 citations. Argentina (61 citations), United Kingdom (66 citations) and Germany (78 citations) also feature prominently among the top contributors to lake citations. In contrast, citations related to oxbow lake are comparatively lower. The United States (59 citations), Argentina (52 citations), and Canada (49 citations) remain leading contributors, while European and Asian countries such as Hungary (43 citations), Australia (45 citations), India (29 citations), and Poland (21 citations) also exhibit growing scholarly engagement (Figure 6). This trend reflects the increasing recognition of oxbow lakes as important yet understudied components of fluvial ecosystems, particularly in relation to biodiversity conversation and hydrological dynamics.

3.2.5. Articles

Figure 9 illustrates the annual scientific production from 2000 to 2021. Overall, the number of published articles has exhibited noticeable year-to-year fluctuations. The most significant increase in scientific output occurred in 2010, with a peak of four articles, marking the highest publication rate during the observation period. Additional production spikes were observed in 2015 and 2018, with three published articles.

Conversely, several years recorded extremely low publication activities, including no articles in 2002, 2006, 2008, 2009, 2013, 2017, and 2019. This pattern reflects an inconsistency in publication trends, potentially influenced by various factors, such as research funding dynamics, shifts in academic policy, or variability in research activities across institutions and researchers.

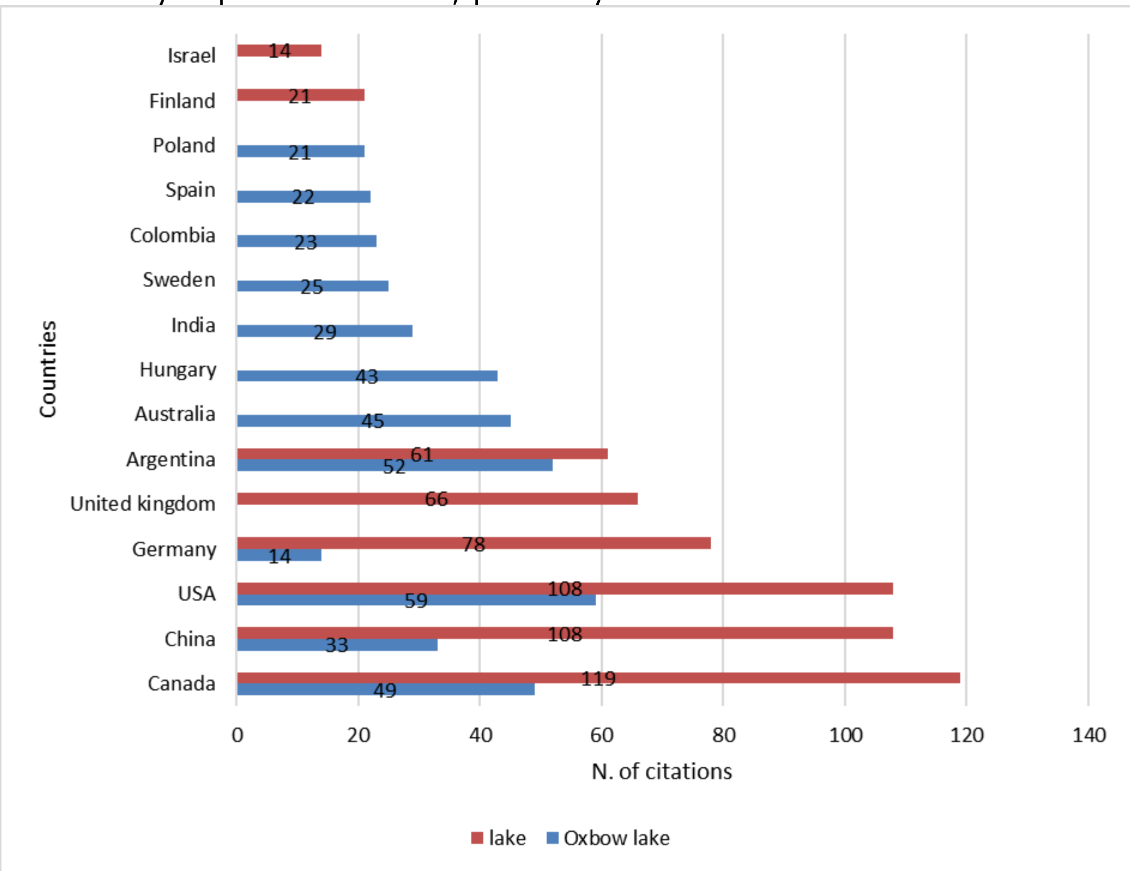

Figure 8. Most Cited Countries between lake and oxbow lake

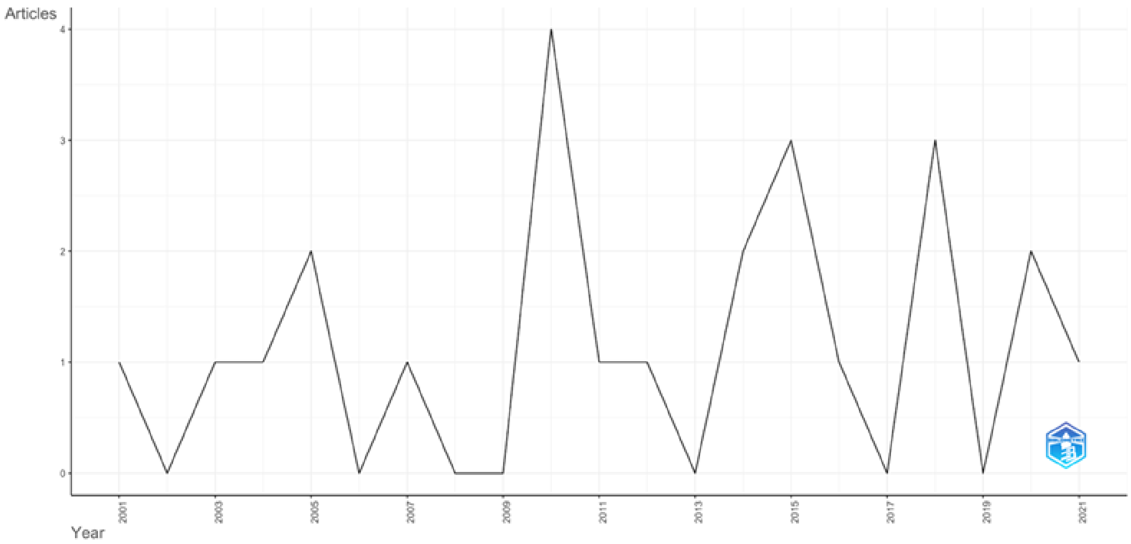

Figure 9. Line Chart of Annual Scientific Production for Diatom and Oxbow Lake

Figure 10 illustrates the annual scientific production trend from 2000 to 2025. In the early 2000s, the number of published articles remained very low, with no publications recorded in several years, such as 2001, 2002, and 2004 to 2008. A noticeable increase began in 2010, with three articles published; the peak occurred in 2012 and 2017, each reaching four articles. The period between 2015 and 2020 reflects a relative stability phase, maintaining a steady output of three articles per year. However, a sharp decline followed after 2021, with no articles published in 2022, a modest recovery to 2 articles in 2023, and only 1 article published in 2024 and 2025. Overall, the scientific production trend revealed a period of growth post-2010, stabilization during the mid-2010s, and a decline in the early 2020s.

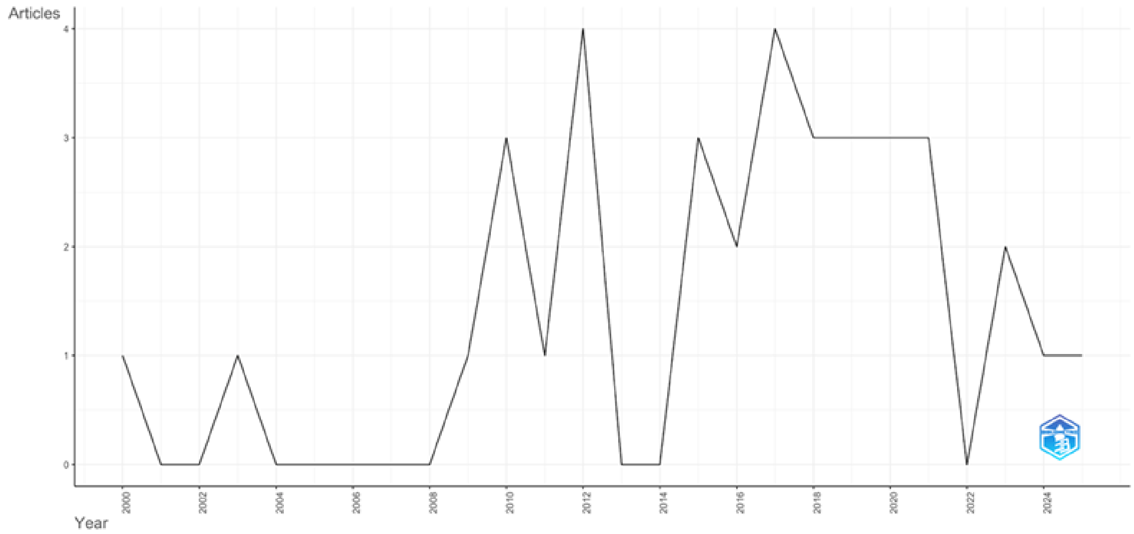

Figure 10. Line Chart of Annual Scientific Production for Diatom and Lake

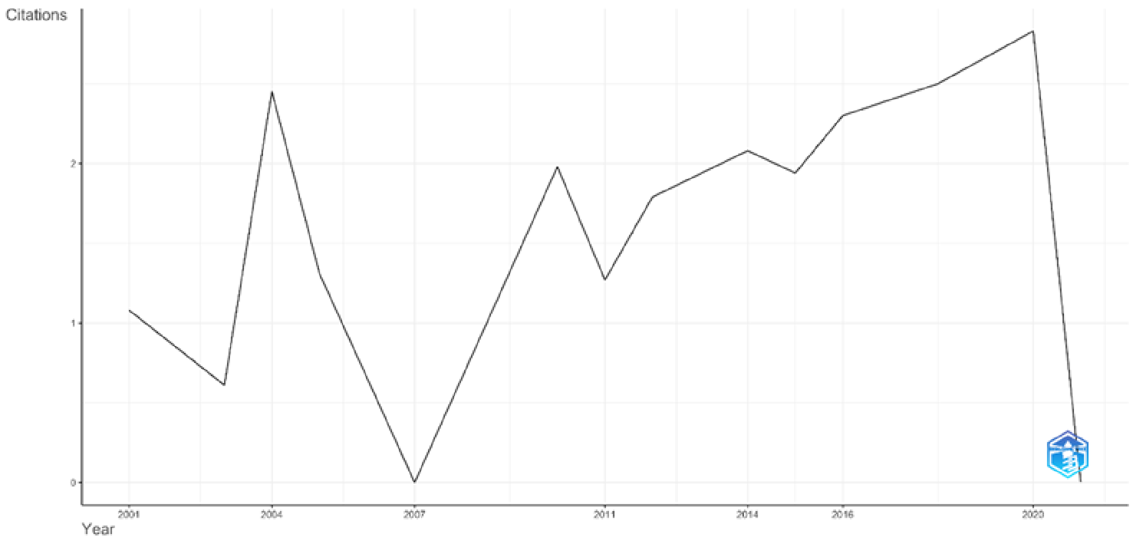

Figure 11. Average Citations per Year for Diatom and Oxbow Lake

In the early 2000s, the average citations per article remained low, fluctuating slightly between 1 and 2. A sharp increase occurred in 2004, reaching a temporary peak at approximately 2.5 citations per article. After a steep decline in 2007, the trend began to rise consistently from 2009 with minor fluctuations. From 2012 to 2020, the average number of citations per year increased steadily, indicating the growing visibility and impact of scientific publications. The highest average was recorded in 2020, approaching 3 citations per article. However, a significant drop was observed following this peak, with citation averages falling to nearly zero by 2022 and 2023 (Figure 11).

The chart in Figure 12 illustrates the trend of the average citations per year from 2000 to 2025. During the early period (2000–2009), citation levels remained stable, averaging between 1 and 1.5 citations per article, reflecting an initial phase of scientific output with moderate visibility. Starting in 2010, a noticeable increase in average citations began, reaching its first peak in 2012–2013, with values ranging between 2.5 and nearly three citations per article. From 2014 to 2018, the trend showed minor fluctuations, with a slight decline, yet remained above 1.5 citations. Another peak occurred in 2019, which was followed by a subsequent decline. After 2022, the graph displays a sharp drop, approaching zero citations in 2024–2025. This is most likely due to the recency of publications in those years, meaning that they have not yet had time to accumulate citations.

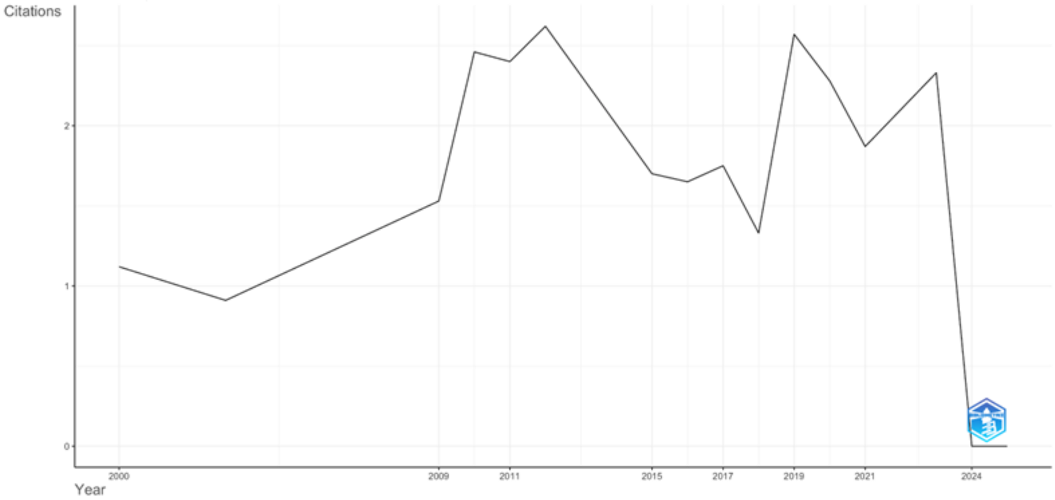

Figure 12. Average Citations per Year for Diatom and Lake

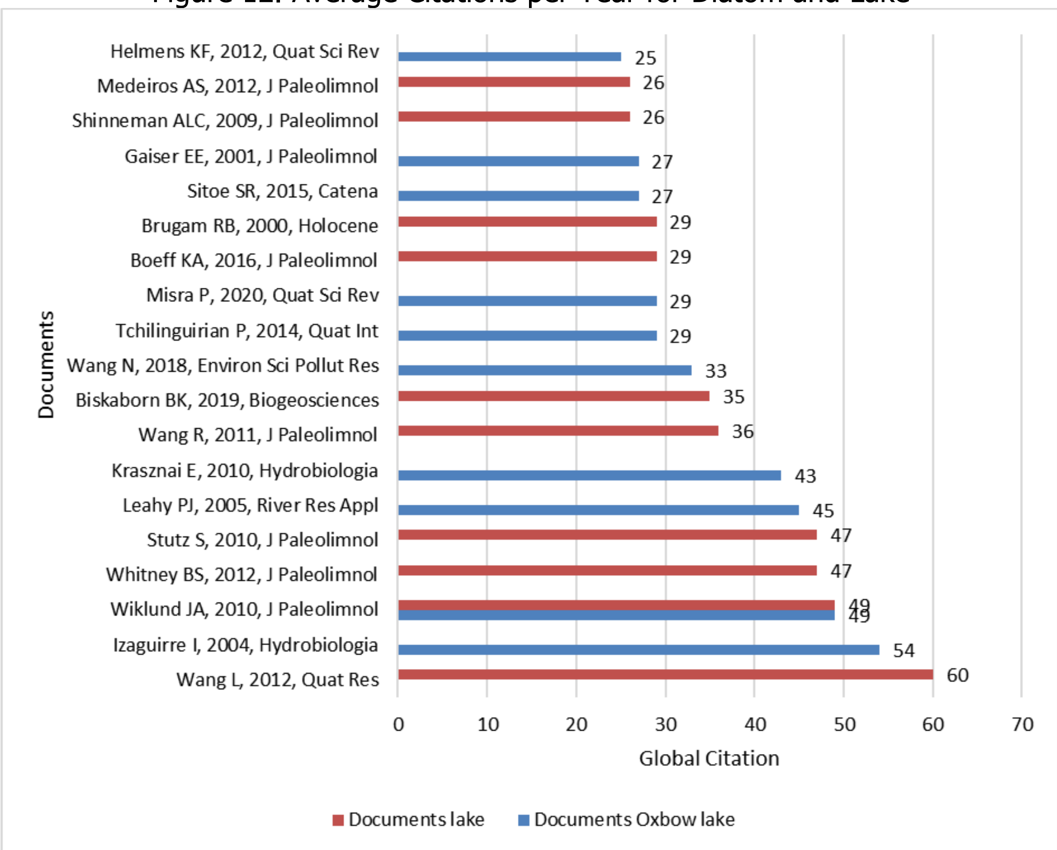

Figure 13. Most Globally Cited Documents between lake and oxbow lake

The bibliometric assessment illustrated in Figure 13 compares the global citation counts of the 20 most-cited documents related to diatom studies in both lake and oxbow lake ecosystems. Citation frequencies range between 25 and 60, reflecting the significant influence of these foundational publications within the field. The most influential contribution is Wang L (2012) published in Quaternary Research, which centers on lake system and has accumulated 60 citations, representing the highest level of global recognition. Similarly, Izaguirre I (2004) in Hydrobiologia (54 citations) reinforces the substantial impact of oxbow lake studies at the upper end of the citation spectrum. Following Overall, citation dominance by studies in the Journal of Paleolimnology, Hydrobiologia, and Quaternary Science Reviews highlights their role as key publication outlets for diatom-based paleoenvironmental research.

3.3. Topic Trend

An analysis of research topic trends revealed that several terms experienced increased usage during specific periods. "algae" emerged as early as 2004 and remained a central focus until around 2010. Terms such as "lakes" and "cyanobacteria" appeared more frequently in 2010. The term "holocene" peaked in usage in 2012. Between 2010 and 2014, there was a notable rise in the use of the terms "bacillariophyta" and "diatom", which showed high frequency and reflected a strong interest in diatom studies and other phytoplankton groups. During the same period, "cyanobacteria" appeared more often, albeit at a lower frequency. In the following years, terms such as "phytoplankton" and "wetland", became increasingly common, followed by "oxbow lake" and "floodplain". These data indicate an evolving research landscape, transitioning from aquatic ecology and environmental change to themes centered on conservation and biodiversity over the past decade (Table 5).

Table 5. Topic Trends for Diatom and Oxbow Lake

Term	**Fre-quency**	**Year (Q1)**	**Year (Med)**	**Year (Q3)**
algae	7	2004	2010	2012
cyanobacteria	5	2010	2010	2018
lakes	5	2010	2010	2016
holocene	8	2005	2012	2016
bacillariophyta	23	2010	2014	2017
diatom	21	2010	2014	2018
phytoplankton	6	2011	2014	2016
wetland	5	2010	2015	2016
diatoms	12	2010	2016	2018
floodplain	12	2013	2016	2018
oxbow lake	11	2012	2016	2019

The analysis of the research topic trends in Table 6 illustrates the evolving focus of scholarly studies from 2010 to 2021. In the early years of this period, terms such as "paleoclimate", "Holocene", and "paleoenvironment" dominated scientific discourse, reflecting a growing interest in past climate reconstruction. Over time, the focus shifted toward themes such as "climate variation", "paleolimnology", and "lacustrine deposit" around 2015–2016, indicating increased attention to the interactions between ancient climates and environments. In subsequent years, new terms such as "bacillariophyta", "bioindicator", and "diatom" appeared with high frequency, signaling a transition in research toward the use of biological indicators for environmental and climate change analysis. From 2017 to 2019, the focus further shifted to contemporary issues, including "climate change", "lakes", "climate change", and "Anhtropogenic-effect". Between 2019 and 2022, topics such as "phytoplankton", "environmental-monitoring", and "Russian federation", became increasingly prominent, reflecting a growing interest in environmental monitoring and regional biodiversity studies, particularly in the Russian Federation. This shift demonstrates that research in paleolimnology and aquatic ecology has increasingly incorporated climate change and conservation issues into analytical frameworks.

Table 6. Topic Trends for Diatom and Lake

Term	Freq-uency	Year (Q1)	Year (Med)	Year (Q3)
paleoclimate	8	2011	2012	2015
holocene	8	2010	2014	2018
paleoenvironment	11	2012	2015	2017
climate variation	6	2013	2015	2016
paleolimnology	16	2012	2016	2018
lacustrine deposit	10	2015	2016	2018
paleoecology	7	2014	2016	2017
bioindicator	35	2012	2017	2020
diatom	33	2010	2017	2020
bacillariophyta	29	2012	2017	2019
climate change	14	2017	2018	2021
lakes	11	2016	2018	2020
Anthropogenic-effect	6	2016	2018	2019
phytoplankton	6	2018	2019	2022
russian federation	6	2018	2019	2022
Environmental-monitoring	6	2018	2020	2021
lake	5	2017	2020	2021

3.4. Keyword

Figure 14 illustrates the distribution of the most frequent or relevant keywords found in studies of lake and oxbow lake, comparing their occurrence for each category. Diatom, bioindicator, and bacillariophyta stand out as the most commonly used keywords for lakes, with exceptionally high counts, while their frequency is noticeably lower yet still prominent for oxbow lakes. Other keywords, such as climate change, paleolimnology, and floodplain, appear frequently in both contexts, although their values are generally higher in the lake category. Keywords such as biodiversity, the United States, and cyanobacteria are mentioned less often across both categories. The data suggest that research on lakes is more strongly associated with terms linked to biological indicators and paleoenvironments compared to oxbow lakes, where these terms appear but with less frequency.

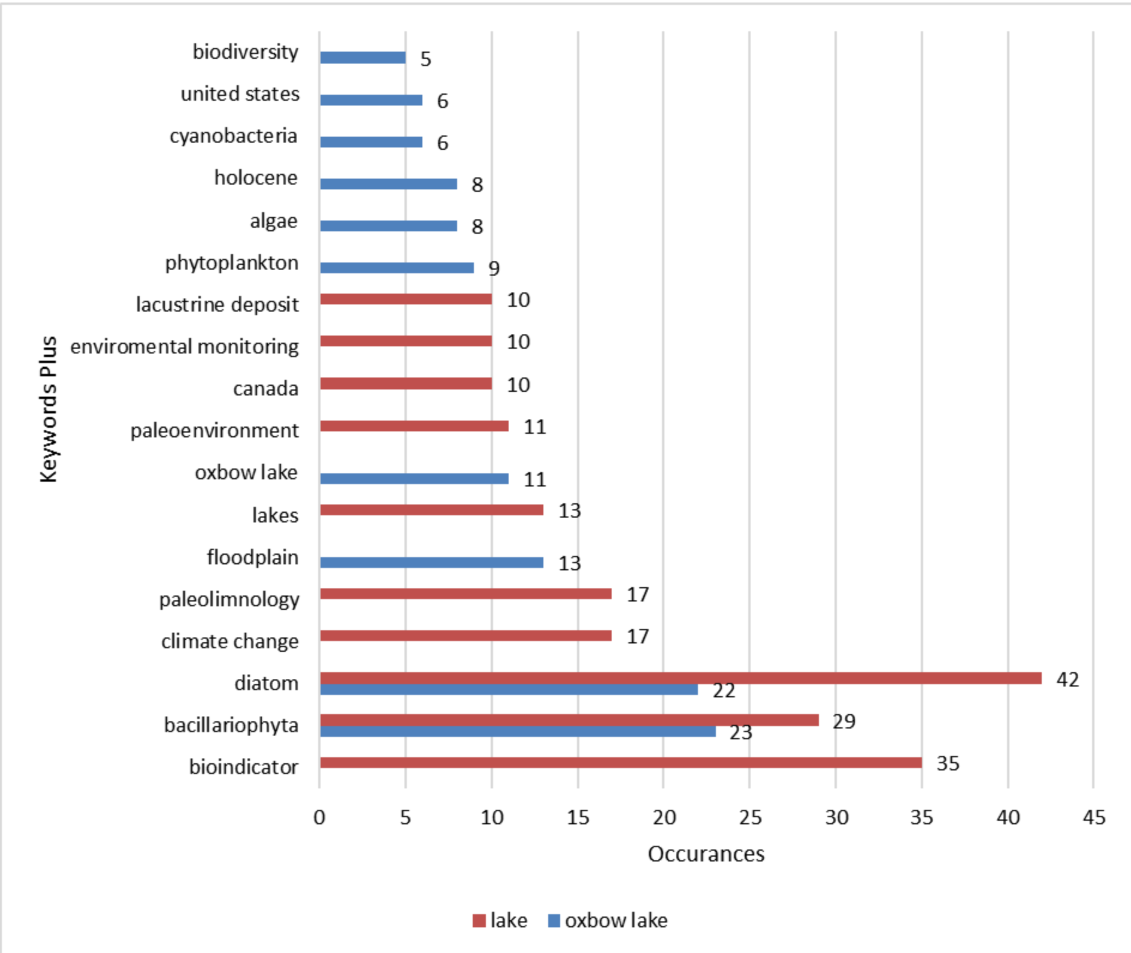

Figure 14. Most Frequent/Relevant Words for lake and oxbow lake

Figure 15. Treemap visualizing the frequency of major terms and topics within diatom research in lacustrine environments, as determined from bibliometric analysis of publications indexed in Scopus. Each box represents a distinct term or topic, with size proportional to the number of publications referencing that term. The largest categories, such as bacillariophyta, diatom, floodplain, oxbow lake, and phytoplankton, reflect dominant research areas in the field. Notably, 'oxbow lake' appears less frequently than broader categories, highlighting a relative gap in focused research on these ecosystems. Colors group related research themes, including taxonomy, ecology, and geography, with percentage values shown for each tile. This treemap allows quick assessment of research priorities and underrepresented areas, supporting the conclusion that, although oxbow lakes are ecologically important, studies specific to these systems remain comparatively limited within the diatom literature. The visualization emphasizes the need for broader research efforts directed toward underexplored habitats such as oxbow lakes.

The treemap in Figure 16 visually depicts the distribution of key research themes and terminology within diatom studies conducted in lacustrine environments, based on a comprehensive bibliometric analysis of articles indexed in the Scopus database. Each rectangle on the treemap corresponds to a specific term or category, with its size proportional to the number of publications in which the term appears, thereby reflecting the prominence of each research focus within the field. Predominant categories, such as diatom, bacillariophyta, and bioindicator, are represented by larger segments, indicating their central significance and extensive discussion in the scholarly literature. Other substantial categories, including climate change, paleolimnology, lakes, and environmental monitoring, highlight continuing research attention to environmental processes and lake ecosystem dynamics. The comparatively smaller segment devoted to oxbow lakes underscores a relative lack of focus on this habitat, suggesting that these ecosystems remain underrepresented in diatom research despite their ecological importance. The use of color serves to separate and clarify different thematic groupings, enabling readers to discern patterns of emphasis and gaps within the research landscape. Collectively, this visualization provides a succinct overview of how scholarly attention has been allocated in diatom-related studies, illustrating established priorities while also evidencing the need for further research devoted to less-studied habitats, like oxbow lakes, within the broader field of freshwater science.

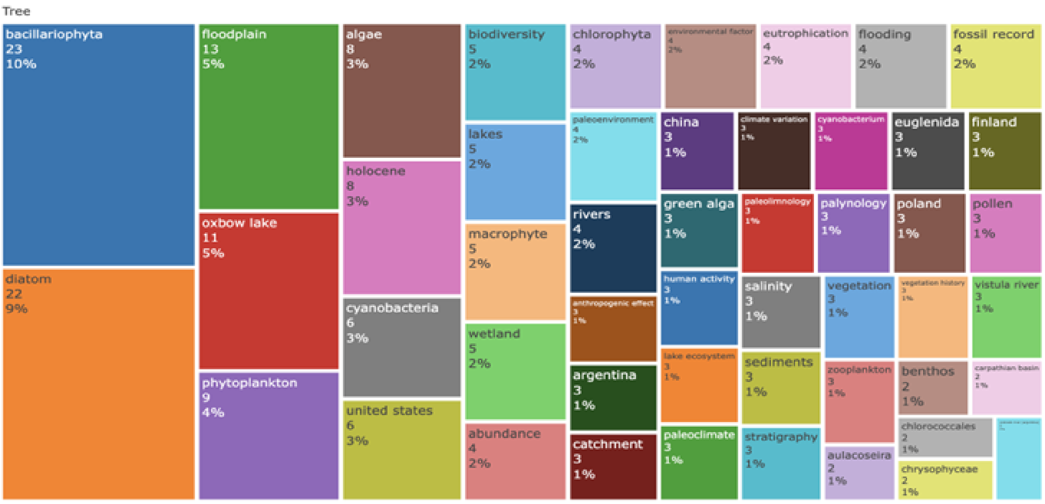

Figure 15. Tree Map for Diatom and Oxbow Lake

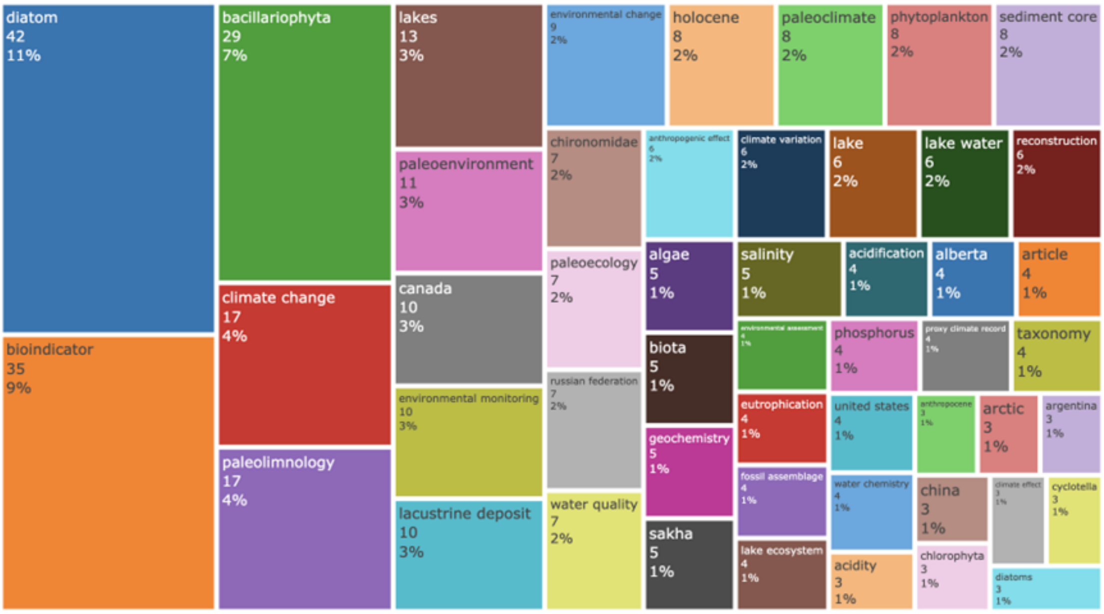

Figure 16. Tree Map for Diatom and Lake

3.5. Future research opportunities on diatom-related topics in lakes and oxbow lakes

Figure 17 presents a thematic map illustrating the position and relationships among the research themes based on their level of development (density) and relevance (centrality). Themes such as "bacillariophyta", "diatom", and "floodplain" occupy the Motor Themes quadrant, indicating that these topics are both significant and well-developed, serving as central pillars in the field. Themes such as "climate variation", "paleoclimate", and "palynology" are located in the lower right quadrant as Basic Themes, suggesting that although they are crucial, they are still undergoing further development. Meanwhile, themes such as "anthropogenic effect", "catchment", and "floods" are situated in the lower left quadrant, categorized as Emerging or Declining Themes, indicating they are underdeveloped and currently play a limited role within the research network. Lastly, themes like "chlorococcales" and "embryophyte" in the extreme lower left quadrant represent specialized topics that are less integrated into the mainstream research flow. This mapping provides a clear overview of the dynamics and priorities of the development of research within the field.

The thematic map in Figure 18 illustrates the distribution of the research themes based on their degree of development (density) and relevance (centrality). Themes such as "climate change", "lakes", and "Canada" are positioned in the Motor Themes quadrant, indicating that these topics are highly relevant and well-developed, serving as primary drivers within this research field. Meanwhile, themes like "bioindicator", "diatom", and "bacillariophyta" are located at the center of the map, reflecting that they are critical general topics but are still undergoing further development. Themes such as "Sakha", "climate effect", and "spatial distribution" appeared in the lower-left quadrant as Emerging or Declining Themes, suggesting that these topics are less central and less developed in the current literature. Overall, the map highlights a primary research focus on the impact of climate change on lakes in the Canadian region, supported by the use of diatoms as environmental bioindicators.

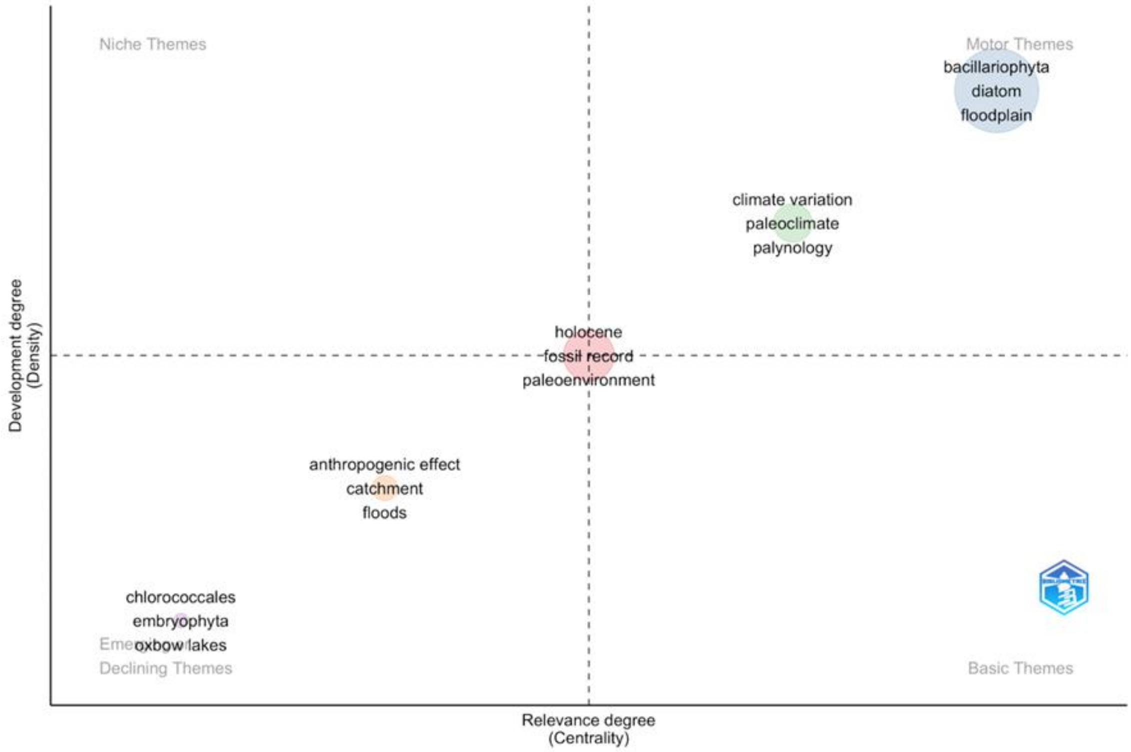

Figure 17. Thematic Map for Diatom and Oxbow Lake

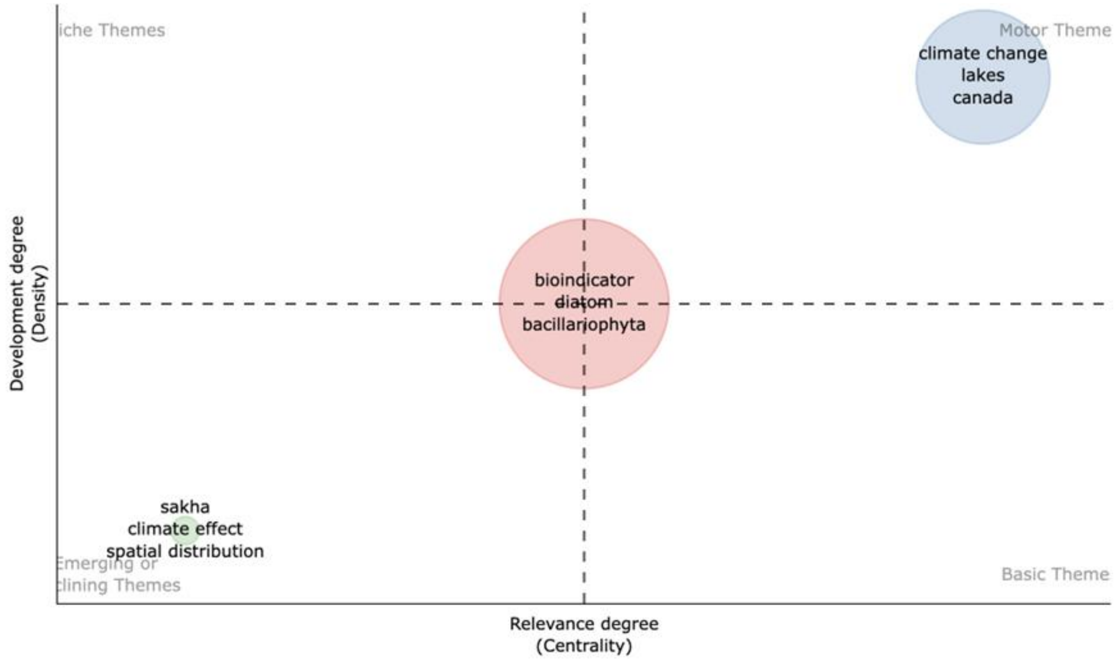

Figure 18. Thematic Map for Diatom and Lake

3.6. Collaboration in bibliometrics

The authors depicted in Figure 19, such as Hall Roland I and Espinosa Marcela A, emerge as central figures in the collaboration network, indicated by the larger node sizes and higher levels of connectivity, reflecting their dominant roles within the network. Other groups led by authors such as Black Jessica L, Deák Csaba, and Farooqui Anjum demonstrate smaller yet solid collaborations within their respective clusters. This visualization suggests the existence of several relatively independent scientific communities, with limited connections between clusters, reflecting the specialization of research themes and more intensive collaboration within specific groups.

As shown in Figure 20, Reavie Euan D and Smol John P are central hubs within the research collaboration network, as reflected by the larger node sizes and extensive connections surrounding them. Researchers such as Genkal Sergey, Barinova Sophia, and Wang Rong also demonstrated significant roles within their respective collaborative clusters, albeit on a smaller scale. Each group formed relatively isolated collaboration clusters, indicating a specialization of research themes or geographical focus within the field. Additionally, several minor collaborative pairs operate with more limited interactions, such as Borel Cmarcela, Del Puerto Laura, Almedinger James E, and Edlund Mark B. This visualization illustrates a fragmented research community structure with minimal connections between clusters but high collaboration intensity within specific groups, reflecting a focused, expertise-driven collaboration pattern.

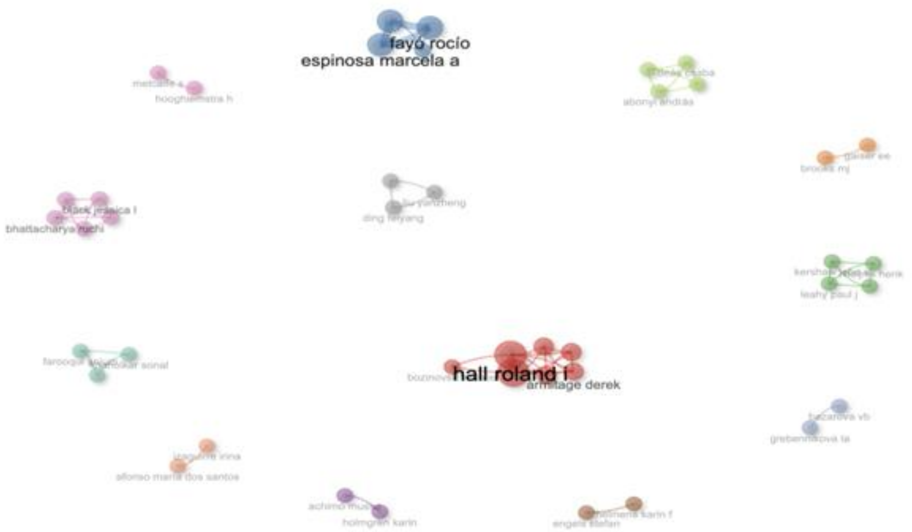

Figure 19. Collaboration Network for Diatom and Oxbow Lake

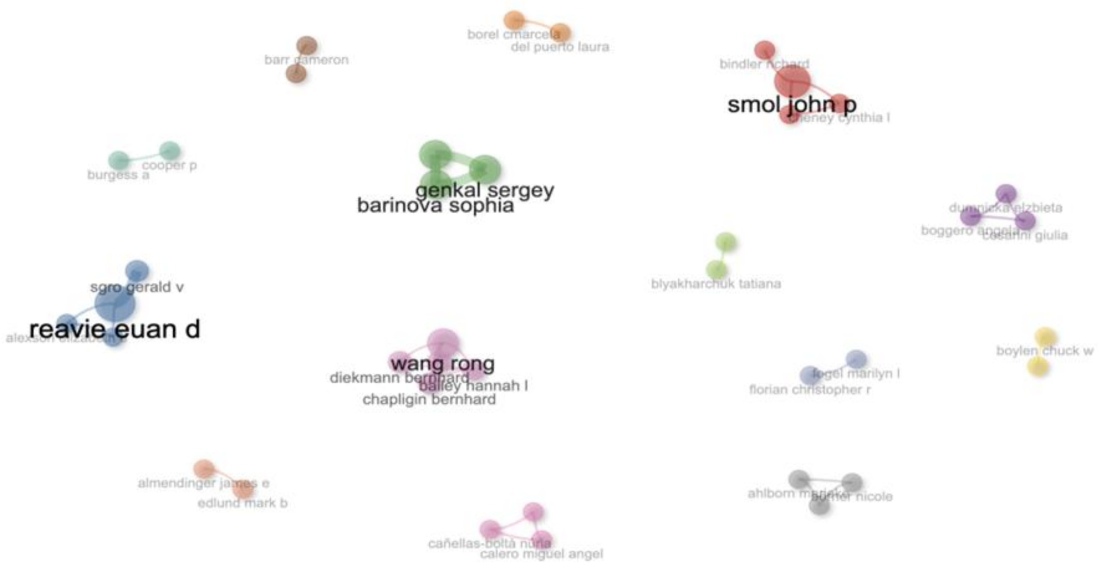

Figure 20. Collaboration Network for Diatom and Lake

Based on the bibliometric analysis, future directions in paleolimnology for lacustrine systems, including oxbow lakes, should emphasize the integration of high-resolution sediment-based records with multi-proxy approaches to illuminate long-term environmental change. Specifically, future work would benefit from collecting continuous sediment cores from oxbow lakes to reconstruct past hydroclimate variability, flood regimes, and land-use impacts over centennial to millennial timescales, and from pairing diatom assemblages with geochemical tracers, isotopic indicators, and sedimentary DNA to improve attribution of climatic versus anthropogenic forcing. Developing regionally calibrated transfer functions for diatoms will enhance quantitative reconstructions of past temperature, nutrient status, and hydrological connectivity in both temperate and tropical oxbow systems. Chronology improvements—through varve analysis, radiocarbon dating, lead-210, and tephrochronology—will enable detection of short-lived environmental episodes. Emphasis on underrepresented regions, particularly tropical and subtropical oxbow lakes, will fill critical knowledge gaps and improve global syntheses. Finally, fostering open data practices by building shared, metadata-standardized paleolimnology databases will facilitate cross-site comparisons, enhance reproducibility, and accelerate the translation of paleo-records into actionable conservation strategies for vulnerable freshwater ecosystems. This direction aligns with the growing recognition of paleolimnology as a powerful tool for understanding long-term ecological dynamics in lakes and for informing adaptive management in the face of ongoing climate and land-use change.

4. Conclusion

This literature review and bibliometric analysis confirm that diatoms play a critical role as bioindicators in freshwater lake ecosystems, especially in monitoring environmental changes, such as climate variability and anthropogenic disturbances. The study revealed a significant increase in scientific output on this topic over the past two decades, with dominant contributions from countries such as the USA, Canada, and Argentina. The analysis also shows that research activity is concentrated in several key publication venues and driven by influential contributors in the field. Research has transitioned from foundational studies on diatom taxonomy to more applied themes, including environmental monitoring and paleoenvironmental reconstructions. Despite their ecological importance, oxbow lakes remain underrepresented in diatom studies, highlighting the potential gap and opportunities for future research. Thematic analyses underscore the need for continued interdisciplinary approaches integrating taxonomy, paleolimnology, and environmental science to support freshwater conservation. This study contributes to a clearer understanding of global research patterns and offers strategic insights for advancing diatom-related studies, particularly within the Indonesian context.

Data availability statement

The data included and used in this study is not confidential and is available upon request.

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Conflict of interests

The authors declare that there are no conflicts of interest related to the submission of this manuscript.

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Author Contributions

SP conducted the investigation, data collection, formal analysis, bibliometric processing, and preparation of the manuscript. **TRS, LK, JJ, MHAF, YY, AA,** and **ŁK** were involved in the conceptualization of the study, contributed to methodological refinement, and critically reviewed and edited the manuscript. All authors read and approved the final version of the manuscript.

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Global Trends and Evolution of Ecotechnology in Textile Wastewater Treatment: 21-Year Bibliometric Analysis

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Abstract: The textile industry supports the global economy, but it produces dye-rich wastewater that poses a threat to ecosystems and human health. Conventional treatment methods are expensive, energy-demanding, and often unsustainable. This study examines global research trends in the application of ecotechnology for textile wastewater treatment from 2004 to 2024. Data were collected from Scopus on August 9, 2025, and analyzed using the PRISMA, Excel, and VOSviewer tools. A total of 413 peer-reviewed English papers were reviewed based on the keywords "ecotechnology" and "textile wastewater treatment." Research output has grown significantly since 2016, driven primarily by India and China. Core topics include constructed wetlands, adsorption, and phytoremediation, while recent studies highlight advanced materials, photocatalysis, nutrient recovery, and water conservation. These developments show a shift toward hybrid systems and circular economy models. Most papers appear in multidisciplinary journals, reflecting the broad and interconnected nature of the field. Yet, significant gaps remain in linking technology with social, policy, and behavioral aspects. Stronger collaboration across disciplines is needed to connect innovation, governance, and local engagement. Such efforts will help make ecotechnology a more sustainable and scalable solution for managing textile wastewater.

Keywords: Adsorption, bibliometric analysis, wetlands, nature-based solutions, textile effluent treatment, sustainability

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1. Introduction

The textile industry is a significant part of the global economy, supporting growth and providing millions of employment opportunities (Castillo-Suárez *et al.*, 2023; H. Khan & Kaur, 2024). Yet, it is also one of the largest sources of water pollution, producing substantial amounts of complex wastewater that harm both the environment and human health. Textile effluents contain toxic and persistent substances such as dyes, heavy metals, surfactants, and organic matter that are difficult to break down (Deng *et al.*, 2020; Gomaa *et al.*, 2023). When released into rivers and lakes without proper treatment, these pollutants damage aquatic life and ecosystems. Dyes block sunlight and slow photosynthesis, while heavy metals build up in sediments and organisms (Ajibade *et al.*, 2023). High levels of nutrients and organic matter lead to oxygen depletion, eutrophication, and loss of biodiversity. Together, these effects disturb the natural balance of ecosystems and weaken the services they provide (Khattab *et al.*, 2020; Zulti *et al.*, 2024). Understanding how technologies for treating textile wastewater have evolved is therefore essential for addressing environmental and social challenges in industrial areas. Because the impacts are severe and widespread, studying research trends in textile wastewater treatment has become increasingly important.

Conventional treatments such as coagulation–flocculation, activated sludge, and chemical oxidation are widely used for textile wastewater (Neto *et al.*, 2024; Odhaib & Jaeel, 2023). However, these methods often need high energy, create large amounts of sludge, and are less effective at removing new contaminants (Al Prol, 2019). These limits show the need for treatment options that are more sustainable, adaptable, and environmentally friendly.

Ecotechnology has emerged as a promising nature-based approach that applies ecosystem principles to solve environmental problems (Camano *et al.*, 2014). By using natural processes and materials, it offers a cost-effective and resilient way to clean wastewater (Aba *et al.*, 2024). In textile wastewater treatment, ecotechnology includes constructed wetlands, adsorption with natural materials, and phytoremediation using aquatic plants. These systems lower pollutant levels, restore ecosystem functions, improve resilience, and support circular economy goals (Vo *et al.*, 2023).

Research on textile wastewater ecotechnology shows strong pollutant removal performance, often reaching over 80% for ammonia and 60% for dyes. These results are achieved through systems such as constructed wetlands and natural adsorbents like bentonite. Combining several ecotechnologies, such as wetlands with adsorption or phytoremediation, has become a promising approach to enhance treatment efficiency (Susanti *et al.*, 2023). However, there are still a few studies that provide a comprehensive overview of the connections between global research trends, collaboration networks, and sustainability outcomes. Most existing reviews focus on technology performance and case studies, without using bibliometric or network approaches to map broader patterns of innovation and cooperation.

Over the past twenty-one years, research on ecotechnology for textile wastewater treatment has experienced rapid growth, driven by global efforts toward sustainability and the development of nature-based solutions. The 21 years from 2004 to 2024 were chosen to illustrate how this field has evolved during key milestones in sustainability, including the Millennium Development Goals (2000–2015) and the Sustainable Development Goals (2015–2030). This timeline offers a clear view of how international collaboration, innovation, and policy focus have impacted the progress and application of ecotechnology in the textile industry.

Even with this progress, many studies still examine ecotechnology in isolation, looking at single case studies or methods without connecting results across different regions (Yusuf et al., 2020). Only a few explore how research networks, innovation sharing, or global collaboration have evolved. Most reviews stay centered on technology, focusing on how well specific methods work and their limitations. They predominantly address the effectiveness, limitations, and operational aspects of particular treatment methods—such as advanced oxidation processes, membrane filtration, biological treatments, and hybrid systems (Ceretta et al., 2021; Jahan et al., 2022; Kallawar & Bhanvase, 2023). To address this gap, we present a systematic bibliometric review covering a 21-year, leading to the following research questions:

1. How has ecotechnology research in textile wastewater treatment developed over the past two decades?
2. Which countries, institutions, and authors have had the greatest influence on this field?

3. Which journals and document types have most supported the spread of this research?
4. What gaps and opportunities remain for future innovation?

This study aims to analyze global publication trends related to the use of ecotechnology in textile wastewater treatment over the past twenty-one years. It identifies the most influential countries, institutions, authors, journals, and main document types. The analysis visualizes research productivity, impact, and thematic links through keyword co-occurrence and overlay analysis. It also highlights research gaps and offers insights for future studies from both global and Indonesia-specific perspectives.

2. Theoretical background

2.1. Ecotechnology

Ecotechnology merges ecological science and engineering to develop solutions for environmental issues and encourages harmony between human activities and natural processes while reducing environmental harm (Jorgensen, 2020; Kangas, 2019). As a nature-based approach, ecotechnology highlights sustainability, resilience, and long-term ecological stability (Costanza, 2012; Mitsch & Mander, 2017; Stoffers *et al*., 2021). It has evolved into a cross-disciplinary approach applied in various fields, including water treatment, agriculture, and natural resource management (Silva, 2023).

Constructed wetlands, ecological agricultural practices, and natural filtration systems are practical applications of ecotechnologies. These approaches utilize plants, microorganisms, and natural materials to perform essential ecosystem functions, such as removing pollutants and maintaining environmental quality (Ji *et al*., 2022; Nuamah *et al*., 2020). The goals are to reduce energy consumption, reduce dependence on chemicals, and restore ecosystem services that support environmental sustainability (Arenas-Castro *et al*., 2018).

A nature-based approach is a sustainable solution that offers environmental, social, and economic benefits while addressing practical challenges (Li & Hai, 2023; Scarpellini *et al*., 2020). It utilizes local resources, promotes community involvement, and combines knowledge (Bauermann *et al*., 2024). These features make it an essential tool for sustainable development and circular economy practices; however, it remains limited by the need for large land areas, seasonal variations that affect performance, and obstacles such as maintenance issues and long startup times. These factors underscore the importance of adaptive management and integrated planning for the effective deployment of ecotechnology (Flores-Nieves *et al*., 2022; Gustafsson *et al*., 2019).

2.2. Textile Wastewater

Textile wastewater produces large amounts of pollutants from dyeing, washing, and finishing processes. Common pollutants include synthetic dyes and Chemical oxygen demand (COD). COD levels are reported from 200 to over 4,000 mg/L, depending on the production process, which exceeds discharge standards (<200 mg/L) (Ariza-Pineda et al., 2023). Dye molecules, with their complex aromatic structures, are highly resistant to natural biodegradation and can persist for long periods in sediments and water bodies (Lin et al., 2023; Vacchi et al., 2017). Additionally, some dyes release toxic or mutagenic byproducts, which increases ecological stress and poses potential long-term risks to human health and ecosystems (Dutta et al., 2024; Lellis et al., 2019; Ramamurthy et al., 2024). The complex composition of wastewater renders single treatment methods ineffective, often necessitating a combination of physical, chemical, and biological approaches.

Conventional methods such as coagulation, activated sludge, and advanced oxidation have been used to reduce pollutants, especially color and COD. However, these methods are not effective since they require a significant amount of energy. Large amounts of sludge also create new challenges for further treatment. Persistent compounds, especially complex synthetic dyes, remain challenging to break down even with these techniques (Ahsan et al., 2023; Nidheesh et al., 2022). These limitations emphasize the need for alternative, more efficient, sustainable, and environmentally friendly solutions.

2.3. Application of Ecotechnology in Textile Wastewater Treatment

Constructed wetlands (CWs) have shown promising results in treating textile effluent by combining plant-based phytoremediation and microbial processes within engineered substrates. Various studies report that CWs achieved 60–85% COD reduction, 65–90% BOD removal, and up to 70–90% dye removal, depending on plant species, system design, and hydraulic retention time (Etana et al., 2025; Hussain *et al.*, 2018). CWs also significantly remove ammonia by up to 70–80%, phosphorus by up to 40–65%, and suspended solids by as much as 80–95% (Henny *et al.*, 2022). Commonly used plants, such as Canna indica, Typha latifolia, and Phragmites australis, play a dual role by directly absorbing nutrients and dyes (Angmo *et al.*, 2024; Klink, 2017; Kumari & Tripathi, 2015), while their root systems provide oxygen and surface area that enhance the microbial degradation of organic compounds (Sheoran & Singh, 2024; Soana *et al.*, 2025).

Different configurations result in different outcomes. Subsurface flow wetlands effectively remove dyes and COD (Herrera-Melián et al., 2020; Sartori et al., 2016). Surface flow wetlands are more effective at reducing suspended solids and nutrients (Ennabili & Radoux, 2022). When combined, these systems form hybrids that provide a more comprehensive treatment, often removing over 80% of pollutants across multiple parameters (Sharma & Malaviya, 2022). Floating wetlands made from Eichhornia crassipes have also shown promising results in removing color and nutrients from ponds and natural water bodies (Sahreen & Mukhtar, 2023). CWs remain a sustainable option for textile wastewater because they are low-cost, produce little sludge, and are easy to maintain. However, challenges still exist, including large land requirements, system optimization, and reduced performance for persistent dye compounds.

Algal systems are gaining wide attention for treating textile wastewater. Both microalgae and macroalgae can remove nitrogen and phosphorus while breaking down synthetic dyes such as Crystal Violet and Reactive Blue through biosorption and biodegradation (Selvaraj *et al.*, 2022). Algal ponds and photobioreactors have demonstrated high nutrient removal rates, achieving up to 96% for nitrogen and 98% for phosphorus, through suspended-solid phase systems and immobilized algae (Özgür & Göncü, 2023; Tang et al., 2018; Yan et al., 2023). This dual ability makes algae suitable for combining wastewater treatment with the production of valuable biomass, which can later be used for biofuels or fertilizers, supporting a circular economy in wastewater management (Khan et al., 2022).

Integrated ecological systems combine plants, microbes, and algae to achieve better performance. These systems utilize multiple biological pathways simultaneously to enhance the removal of pollutants. Hybrid wetlands that combine wetland plants with algae have shown strong results in removing dyes and nutrients. Such integrated ecotechnologies are practical, sustainable, and increasingly used in pilot and full-scale textile wastewater treatment projects (Dell'Osbel *et al.*, 2020).

3. Materials and Methods

Previous studies show that bibliometric analysis usually includes three main steps: defining the research question, doing the analysis, and presenting the results (Donthu *et al.*, 2021). In this study, the research question is introduced in the Introduction section, while the analytical steps, based on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, are illustrated in Figure 1. The findings are presented and discussed in the Results and Discussion section. The PRISMA framework provides a clear and structured process for identifying, screening, and selecting studies. This method ensured that only relevant and reliable publications were included in the analysis.

3.1. Setting Search Items

A bibliographic search was conducted in the Scopus database for peer-reviewed literature across scientific disciplines. Scopus was chosen because it offers reliable indexing, broad journal coverage, and accurate citation tracking for global research (Baas *et al.*, 2020). The search focused on publications related to "ecotechnology" and "textile wastewater treatment." Main keywords were combined with synonyms such as "textile industry", "textile wastewater", "ecotechnology", "environmentally friendly technology", and "constructed wetlands". Data were collected on 9 August 2025 for studies published between 2004 and 2024.

3.2. Inclusion Criteria and Article Selection

The inclusion criteria covered peer-reviewed English papers that examined ecotechnology in wastewater or textile effluent treatment. Exclusion criteria were applied to eliminate studies that did not address ecotechnology or nature-based treatment methods. Articles were excluded if they did not discuss approaches such as constructed wetlands, phytoremediation, biosorbents, biochar, microbial-based treatment, aquatic macrophytes, or similar ecological technologies applied to textile wastewater. A language filter limited the dataset to English publications from 2004 to 2024. During screening, 19 non-English papers were removed from the original 432 records. The final dataset comprised 413 articles, which were used for detailed analysis.

3.3 Conducting Initial Data and Bibliometrics Analysis

The dataset was organized in Microsoft Excel to support descriptive statistical analysis. This analysis shows publication trends, citation counts, major journals, leading institutions, contributing countries, and document types. The results provide an overview of research growth, productivity, and global distribution. Bibliometric mapping and network analysis were carried out using VOSviewer version 1.6.19. The analysis included keyword co-occurrence, overlay visualization, and co-authorship mapping. The mapping highlights research themes, emerging topics, and collaboration networks among authors. Overlay and density maps reveal a shift from traditional approaches to modern, sustainable technologies. Together, these results give a clear picture of the research landscape and connections in textile wastewater studies.

4. Results and Discussion

4.1. Research Trends by Year

Publication trends over the last 21 years show a clear rise in studies on ecotechnology for treating textile wastewater (Figure 2). Between 2004 and 2016, research activity was limited, marking an early stage with little academic attention (Halepoto *et al*., 2022; Islam *et al*., 2024). After 2017, the number of studies began to grow steadily and increased sharply after 2019. This growth reflects the expanding interest in sustainable, nature-based approaches such as constructed wetlands and integrated systems (Behera *et al*., 2021; Hussain *et al*., 2018, 2019). Research from the past five years highlights the increasing importance of ecotechnology in addressing environmental issues associated with textile production (Rahman *et al*., 2020). The steady increase in studies shows that this topic has become a key area for researchers, practitioners, and policymakers to explore and apply (Bahara *et al*., 2025).

Figure 3 shows the different patterns between research growth and academic influence. From 2004 to 2010, citations peaked in 2005 (3,287) and 2007 (3,291), while publication numbers were still low. These early studies had a profound impact and laid the foundation for subsequent research (Holkar *et al*., 2016). Between 2011 and 2018, citation counts declined and fluctuated at lower levels, despite the number of publications continuing to rise. Each new paper added to the field but had less individual influence. Since 2019, research output has increased significantly, reaching over 60 papers per year in 2022–2023. This steady rise indicates a growing global interest in ecotechnologies for treating textile wastewater. Citation numbers remain moderate, suggesting that the field is now more diverse, with broader participation rather than being driven by only a few landmark studies.

The analysis shows that research on ecotechnology for textile wastewater treatment has entered a mature phase. Publications have proliferated, and citations now appear across a broader range of studies. Research is becoming more diverse, moving beyond dependence on a few early works. Similar observations were made by Sharma and Malaviya (2022), who noted topic expansion and stronger international collaboration as signs of progress in the field.

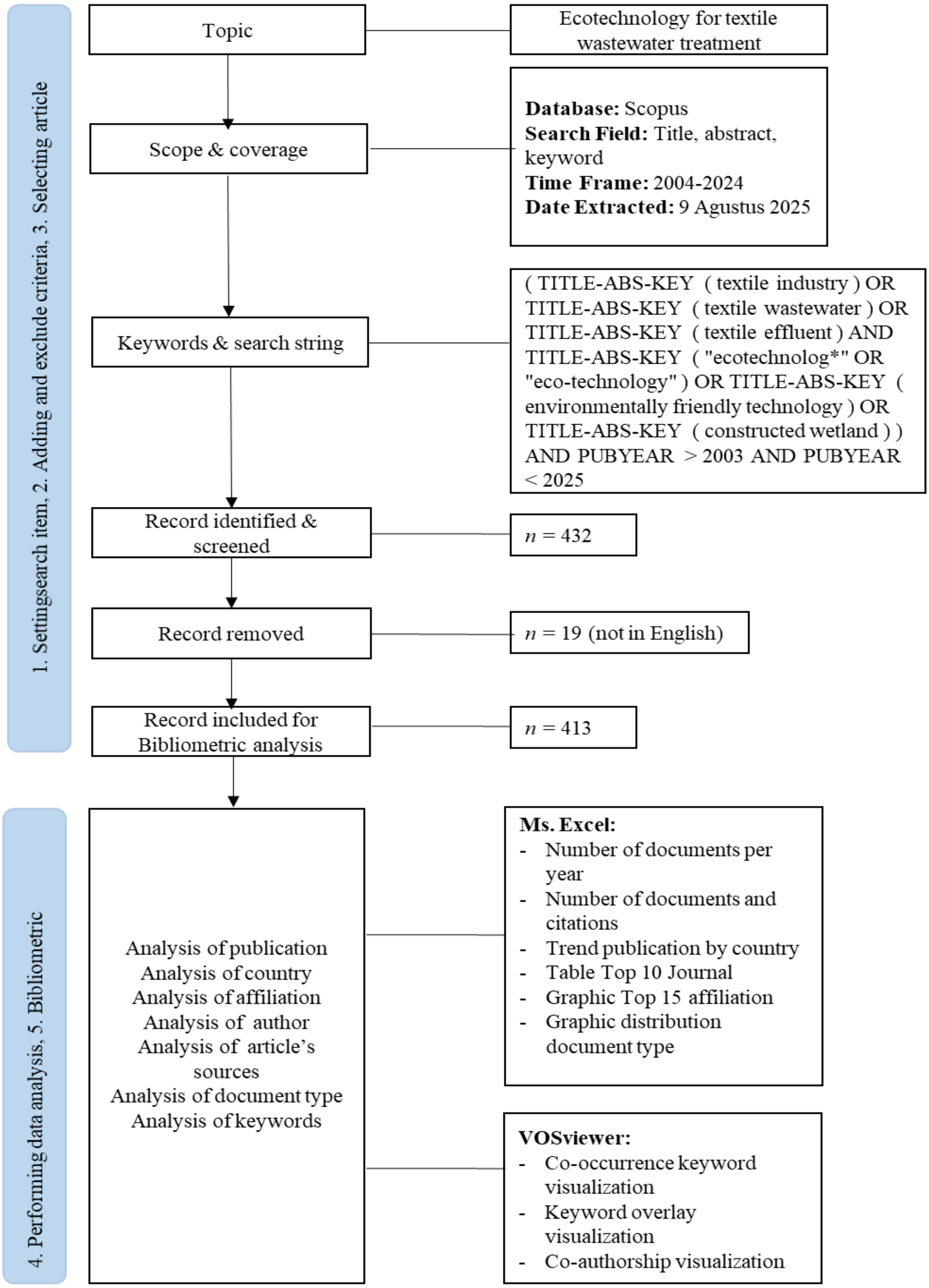

Figure 1. Flowchart of the process of selecting papers for bibliometric analysis

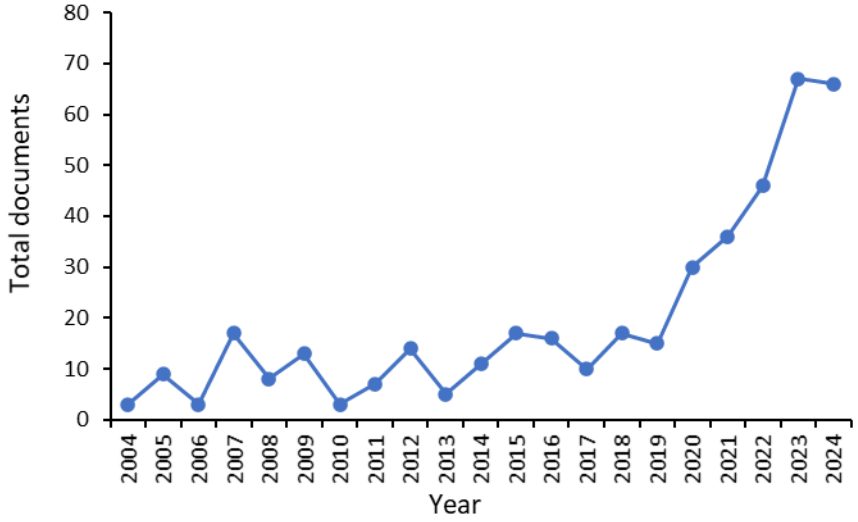

Figure 2. Development of ecotechnology publications for textile wastewater treatment 2004-2024

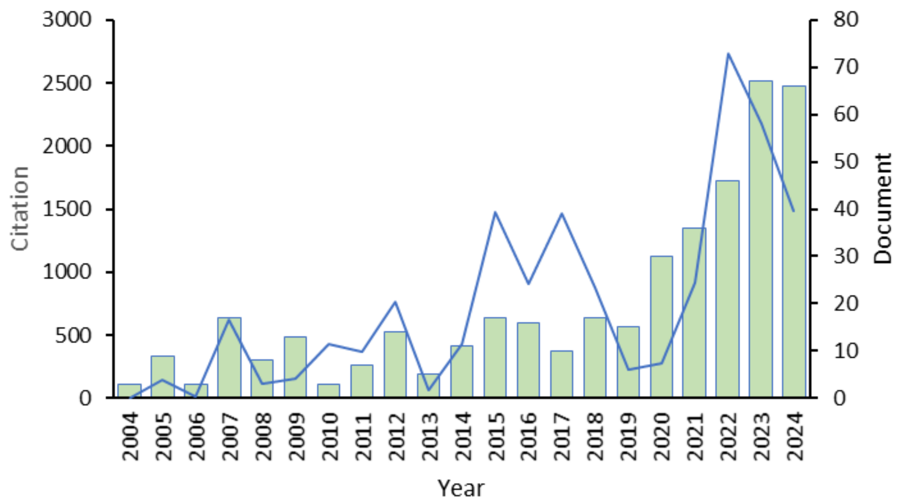

Figure 3. Number of documents and citations on textile wastewater treatment ecotechnology in the last 21 years

4.2. Geographical Distribution of Research

The global distribution of studies on ecotechnology for textile wastewater treatment shows apparent regional differences (Figure 4). Asia leads the field, reflecting its role as the center of textile production. North America and Europe contribute at moderate levels, while South America, Africa, and Oceania show limited research activity. This pattern suggests that research is concentrated in regions facing high industrial activity and intense environmental pressures.

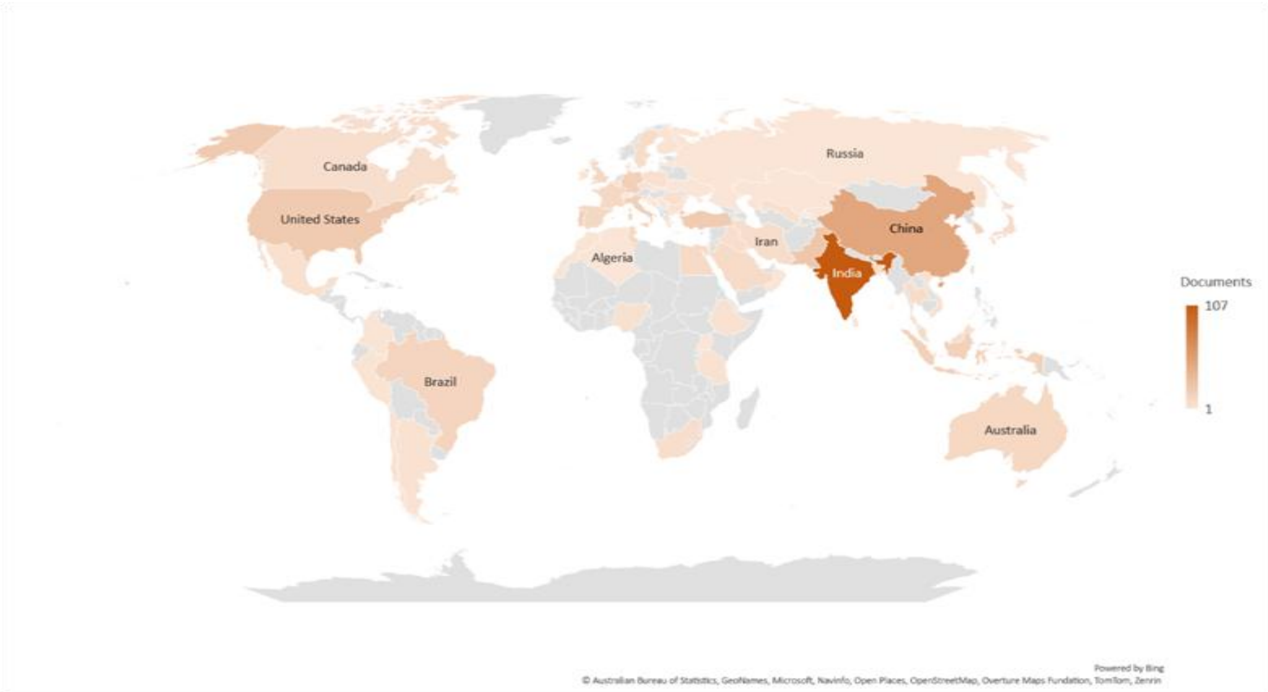

Figure 4. Global distribution of publications on ecotechnology for textile wastewater treatment over the past 21 years

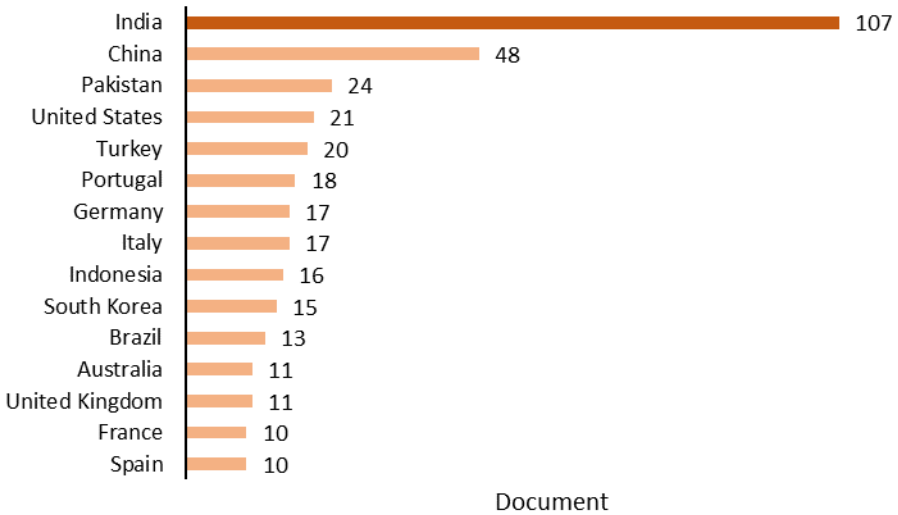

Figure 5. Number of documents on ecotechnology for textile wastewater treatment from up to 15 countries worldwide.

At the country level (Figure 5), India leads with 107 publications, reflecting its large textile industry and ongoing challenges in waste management (Pattnaik *et al.*, 2018). China follows with 48 papers, confirming its major role in textile production and growing commitment to sustainable processing (Lyu *et al.*, 2021). Pakistan (24) and the United States (21) also contribute significantly, illustrating that both developing nations face industry challenges and developed countries possess strong research capacities and robust environmental regulations. Turkey (20) and several European countries, such as Portugal (18), Germany (17), and Italy (17), demonstrate active participation, supported by both academic and industrial interest in sustainable textile technologies.

In Asia, alongside India and China, Indonesia (16) and South Korea (15) also made significant research contributions. This shows that awareness of textile wastewater issues is growing in countries with expanding industries. From other regions, Brazil (13) represents South America, while Australia (11) reflects the continent's active role in Oceania. The United Kingdom (11), France (10), and Spain (10) complete the top 15, demonstrating Europe's collective effort to promote sustainable textile wastewater management globally.

Asia's leading role in this field shows that the growth of ecotechnology research relies not only on advanced technology but also on how accessible, affordable, simple, and practical it is for real-world use (Sohaimi *et al.*, 2023). India emphasizes practical applications using local materials, while China combines simple methods with innovations suited for large-scale industries (Gyamfi et al., 2024; Geng *et al.*, 2021). The rapid progress of research in Asia reflects a close link between local environmental needs and global sustainability goals.

4.3. Analysis Based on Article Sources

Publications on ecotechnology in textile wastewater treatment are published in numerous journals and conference proceedings. This indicates that both academic journals and conferences play a crucial role in disseminating knowledge in this field. The IOP Conference Series: Earth and Environmental Science was the leading platform, highlighting the value of conferences in presenting new ideas. Among peer-reviewed journals, Water Science and Technology (9 papers) and Environmental Science and Pollution Research (8 papers) were the most active in publishing studies on applied environmental engineering and pollution control.

Table 1 shows that high-impact journals, such as Science of the Total Environment and Chemosphere, demonstrate how ecotechnology research bridges different scientific fields. Technical journals, such as the Journal of Water Process Engineering and Desalination and Water Treatment, focus on the engineering aspects of sustainable treatment technologies. The Journal of Cleaner Production links this work to sustainability and circular economy goals, while the Journal of Hazardous Materials highlights concerns about toxicity and risk control. Ecological Engineering emphasizes the value of nature-based systems, such as constructed wetlands, in improving wastewater treatment. Together, these journals demonstrate that ecotechnology research is shifting from a primarily technical approach to one that also incorporates environmental sustainability. This expands earlier studies that focused more on technology than on ecological integration (Behera *et al.*, 2021; S. A. R. Khan *et al.*, 2022).

Table 1. Top 10 leading publication sources on ecotechnology for textile wastewater treatment

No	Journal Name	Number of documents
1	IOP Earth and Environmental Sciences Conference Series	11
2	Water Science and Technology	9
3	Environmental Science and Pollution Research	8
4	Science of the Total Environment	8
5	Chemosphere	7
6	Journal of Water Process Engineering	7
7	Desalination and Water Treatment	6
8	Journal of Cleaner Production	6
9	Hazardous Materials Journal	6
10	Ecological Engineering	5

4.4. Analysis by Affiliation

Author affiliations reveal the distribution of research on ecotechnology across global institutions. Figure 6 illustrates the primary organizations most frequently associated with publications in this field. The National Natural Science Foundation of China (NSFC) leads with 17 publications, followed by the Higher Education Commission of Pakistan (HEC) and the University Grants Commission (UGC) with nine each. The Ministry of Science and Technology, India (MoST), contributed eight papers, while Portugal's Fundação para a Ciência e a Tecnologia (FCT) supported seven, and India's Science and Engineering Research Board (SERB) produced six. Other contributors include CAPES (Brazil) and China's National Key

Research and Development Program (NKRDP), each with five papers. The China Scholarship Council (CSC) and TÜBİTAK (Turkey) followed with four, while CNPq (Brazil), the European Regional Development Fund (ERDF), FAPESP (Brazil), the Japan Society for the Promotion of Science (JSPS), and King Saud University (KSU, Saudi Arabia) each produced three.

This pattern indicates that support for ecotechnology research extends not only to developed nations but also to emerging economies with substantial textile industries. Countries such as China, India, Pakistan, Brazil, and Turkey play active roles in developing innovative and sustainable solutions. Their growing participation reflects the global importance of ecotechnology and its shared goal of improving wastewater management worldwide (Urbina-Suarez *et al.*, 2024).

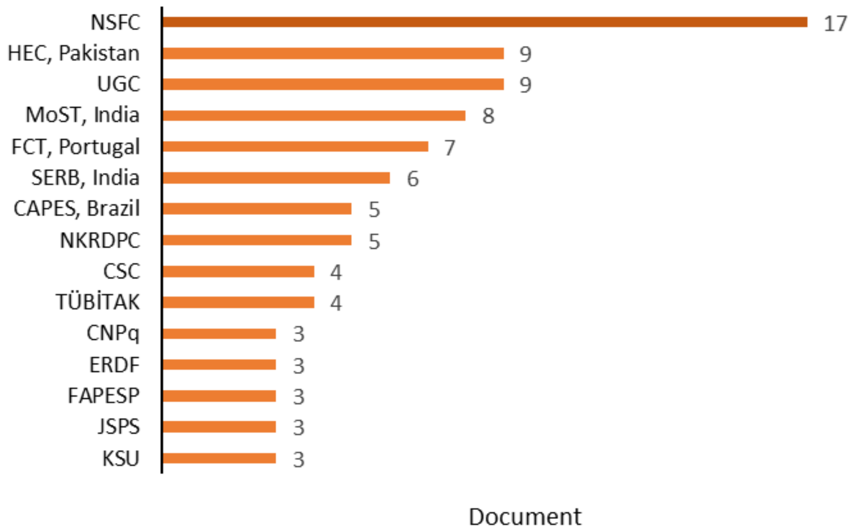

Figure 6. Top 15 affiliates researching ecotechnology for textile wastewater treatment.

4.5. Analysis by Document Type

The distribution of document types (Figure 7a) shows that most publications are research articles (55%), followed by reviews (18%), book chapters (15%), and conference papers (9%). A smaller portion includes books (2%) and conference reviews (1%). The large share of articles shows a focus on publishing original research, while the many reviews indicate a growing effort to summarize existing studies (Ruiz-Sánchez *et al.*, 2024). The share of book chapters suggests a wider dissemination of ecotechnology work in academic volumes, and the conference papers demonstrate the value of academic meetings for sharing early results and fostering collaboration.

The subject area distribution (Figure 7b) shows that Environmental Science leads (23%), followed by Engineering (16%), Materials Science (12%), and Chemical Engineering (9%). Other active areas include Chemistry (7%), Business and Management (6%), Energy (5%), Biochemistry and Molecular Biology (5%), and Agricultural and Biological Sciences (5%). In contrast, Earth and Planetary Sciences (3%), Immunology and Microbiology (2%), Medicine (2%), Physics and Astronomy (2%), Computer Science (2%), and Social Sciences (1%) contribute less. The strong presence of environmental and engineering fields reflects a focus on practical, technology-driven solutions such as new adsorbents, catalysts, and treatment systems. The more minor role of social sciences points to a gap in understanding the socioeconomic, policy, and behavioral factors that influence the adoption of ecotechnologies—a pattern also seen in broader environmental research (Abdullah & Azizan, 2024).

Ecotechnology research is still primarily led by technical work, with substantial input from natural science and engineering fields. Progress in the future will depend on teamwork across disciplines that connects new technology with policy and social understanding. This approach is crucial for achieving tangible improvements and sustainable results in textile wastewater management.

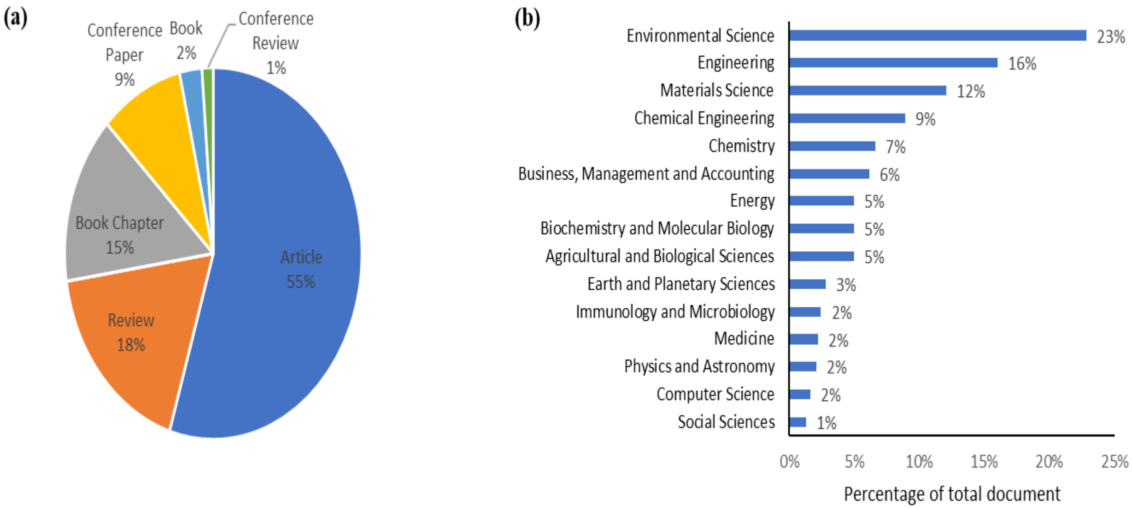

Figure 7. Distribution of publications on ecotechnology for textile wastewater treatment by (a) document type and (b) subject area.

4.6. Analysis by Author

The co-authorship network highlights the collaborative structure of research on ecotechnology for textile wastewater treatment over the past 21 years, considering only authors with at least three publications (Figure 8). Each node represents an author (with size reflecting publication volume), links indicate co-authorship ties, and colors represent collaboration clusters, which often align with thematic or regional research groups (Ariel Xu & Chang, 2020). The green cluster is the largest, with Afzal M. and Arslan M. leading strong partnerships with colleagues such as Iqbal S. and Rehman K., who study phytoremediation and constructed wetlands. The red cluster, centered on Han W. and Wang X., represents a major Chinese group focused on microalgae and nutrient recovery. The blue cluster, led by Rodrigues L.R. and Oliveira G.A., highlights wetland and natural treatment research in Europe and South America. Smaller groups include the yellow cluster (Asghar H.N. and Mohsin M.) and the purple cluster (Ali S. and Rizwan M.), which explore microbial and plant-based treatment systems.

Afzal and Han are key leaders in collaboration networks, each leading strong research hubs in South Asia and China. Their work shows that regional partnerships drive much of the progress in ecotechnology for textile wastewater treatment, while smaller teams add focused expertise that expands the field’s diversity (Scherbakova & Bredikhin, 2021).

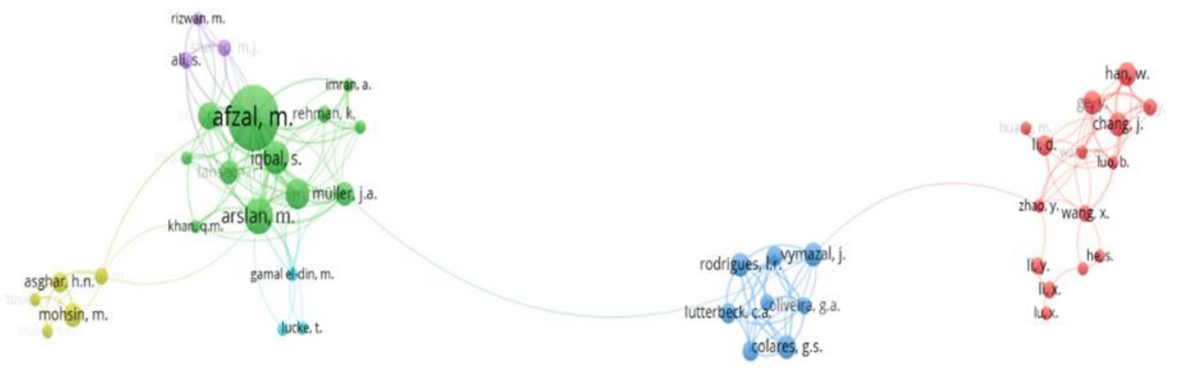

Figure 8. Co-authorship network of researchers working on ecotechnology for textile wastewater treatment over the past 21 years

4.7. Analysis Based on Keywords

The keyword co-occurrence map in Figure 9 shows a visual overview dividing research into four main clusters. The blue cluster represents environmental engineering, marked by keywords such as wastewater treatment, constructed wetlands, COD, and waste. This cluster highlights the dominance of studies using constructed wetlands to remove COD, nitrogen, and heavy metals (Hussein, 2023; Saba *et al.*, 2015). The red cluster focuses on the textile industry, featuring terms like dyes, adsorption, and photocatalysis. It reflects the rise of advanced materials and hybrid adsorption–photocatalytic techniques for degrading synthetic dyes in real wastewater (Munonde *et al.*, 2025). The green cluster includes biological approaches such as bioremediation, phytoremediation, and enzymes, showing the role of microbes and plants in breaking down dyes and transforming pollutants (Parihar *et al.*, 2022). The yellow cluster, though smaller, centers on pollutants like nitrogen and heavy metals, and includes terms such as biochar and water conservation. It points to targeted removal strategies tested in horizontal-flow wetlands and adsorption-based studies (Junio *et al.*, 2024).

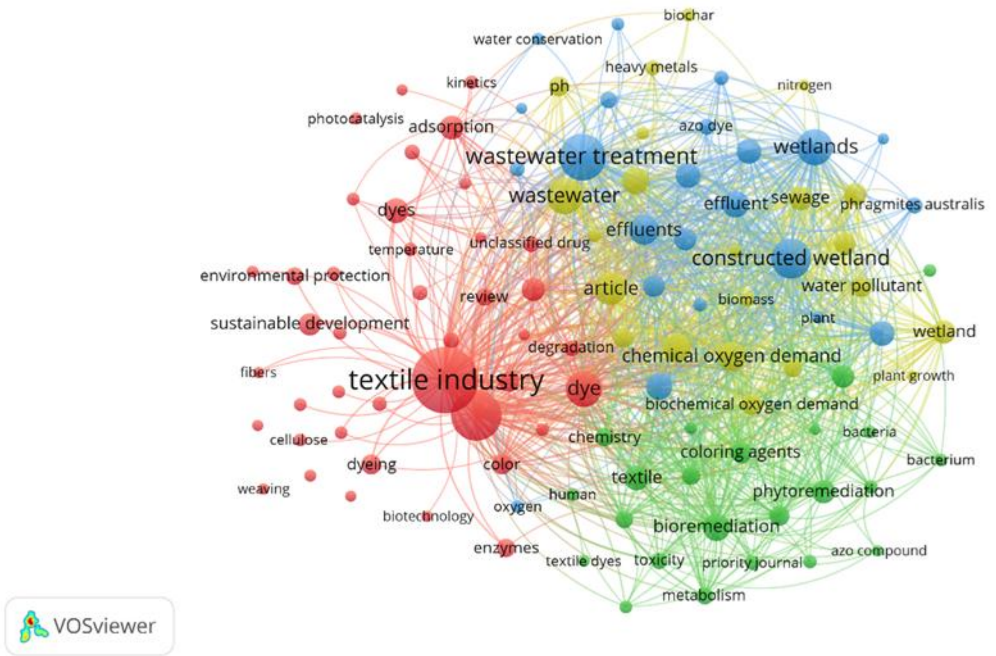

Figure 9. Visualization of frequently appearing keywords in ecotechnology for textile wastewater treatment over the past 21 years

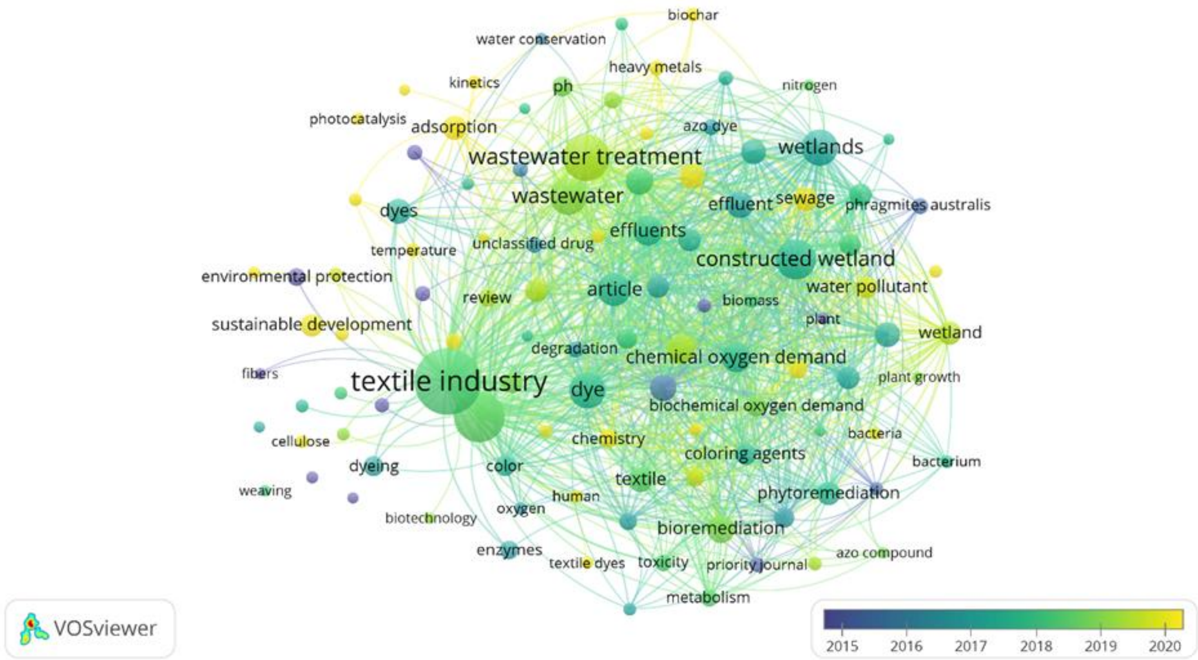

Figure 10. Visualization of overlays that frequently appear in ecotechnology for textile wastewater treatment over the past 21 years

The overlay map in Figure 10 illustrates the evolution of research themes in textile wastewater treatment over time. Early work from 2015 to 2017, shown in green and blue nodes, focused on the textile industry, wastewater treatment, constructed wetlands, and bioremediation. More recent studies from 2019 to 2020, shown in yellow, highlight growing interest in biochar, heavy metals, pH, adsorption, photocatalysis, water conservation, and nitrogen. This change marks a move toward material-based methods, targeted contaminant removal, and sustainable water management. Interest in biochar and photocatalysis reflects the search for affordable, high-performance adsorbents and light-driven treatment processes (Fazal *et al.*, 2020; Jebelli *et al.*, 2024). Growing attention to water conservation and nitrogen control also shows a focus on resource recovery and nutrient reuse (Wongkiew *et al.*, 2024). Overall, these trends show a shift from traditional methods to innovative, multifunctional, and eco-friendly technologies that support circular economy goals and sustainable development.

4.8. Implications and future research

This section discusses the main research gaps found in the bibliometric analysis and outlines future directions at both global and Indonesia-specific levels.

4.8.1. Global Perspective

The bibliometric review shows that research on ecotechnology for textile wastewater treatment has become more diverse and widespread, yet several gaps remain. Most studies still focus on technical and engineering aspects, with limited attention to policy, social, and community factors that are necessary for long-term sustainability. Although Asian countries have made significant progress by linking local environmental challenges to global sustainability goals, the absence of global comparative frameworks makes it challenging to integrate regional findings into shared strategies. Recent studies highlight growing interest in materials such as biochar and in processes like adsorption and photocatalysis. However, questions about their long-term performance, scalability, and environmental impact remain unanswered. These issues highlight the need for collaboration across disciplines and sectors to bridge the gap between technological progress and policy and social relevance.

Hybrid systems that combine adsorption, photocatalysis, and biological treatment show strong potential for industrial wastewater. Future research should also explore nutrient recovery, in situ remediation, pH stabilization, and ecological monitoring using bioindicators (Sethulekshmi & Chakraborty, 2021). Broader collaboration and investment in nature-based systems—such as constructed wetlands and floating treatment beds—are gaining global attention and deserve continued support.

4.8.2. Indonesia-Specific Context

Indonesia's tropical water systems face unique challenges due to seasonal monsoons, high pollution loads, and the presence of small-scale industries like batik production (Daud *et al.*, 2022; Widyarani *et al.*, 2022). These conditions require low-cost, adaptable treatment systems that combine science, field application, and supportive policy (Sutapa *et al.*, 2021). Hybrid systems designed for Indonesia's conditions, such as phytoremediation–adsorption methods using native plants like *Canna indica* and *Vetiveria zizanioides*, supported by local materials like bentonite and zeolite, have shown promising results. Studies report that Floating Treatment Wetlands (FTW), Constructed Wetlands (CW), and fixed-bed reactors can significantly reduce COD and dye concentrations (Zulti *et al.*, 2025). Using bioindicators like *Daphnia magna* helps assess both chemical and ecological outcomes.

Nature-based systems are suitable for small and medium-sized enterprises, especially in textile and batik production (Pratiwi *et al.*, 2018). Pilot projects in West Java demonstrate that CW and FTW units can effectively lower organic matter, dyes, and nutrients. Locally sourced bentonite and zeolite enhance the system's stability, particularly during the rainy season when pollutant loads increase.

Policy and funding programs should formally recognize nature-based solutions as key tools in national wastewater management. Existing Ministry of Environment (KLH) regulations on constructed wetlands could be expanded to encourage their wider use in the textile and batik sectors. Collaborative, cluster-based models, such as those in Pekalongan and Solo, which combine anaerobic pre-treatment, CW/FTW systems, and mineral-based polishing, offer practical examples for sustainable and affordable industrial wastewater management (Effendi *et al.*, 2018; Rahmadyanti & Wiyono, 2020).

5. Conclusion

This study shows that ecotechnology is becoming increasingly important for managing textile wastewater worldwide. Research has moved from traditional engineering toward new, sustainable methods that fit circular economy goals. The analysis gives a clear picture of research growth and global cooperation, especially across Asia. Still, social, policy, and economic issues are rarely explored. These gaps slow large-scale use and real-world application. Future studies should include life-cycle assessment, better policy support, and locally designed hybrid systems. Work in developing countries like Indonesia is needed to connect environmental innovation with community and economic benefits. Together, these efforts will make textile wastewater management more sustainable and practical.

Data availability statement

The data included and used in this study is not confidential and is available upon request.

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Conflict of interests

All authors declare that they have no conflicts of interest related to the writing or submission of this manuscript.

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Author Contributions

FZ, as the primary contributor, conceptualized the study and data analysis and wrote the original article. **DI, AMF**, and **DS** participated in the manuscript writing, review, editing, and supervision.

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Integrated Field Theoretical Evaluation of Sediment Pond Efficiency in a Tropical Mining Catchment

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Abstract: Sediment ponds in coal mining operations serve as critical infrastructure for wastewater management. A major challenge in their operation is excessive sediment accumulation, which is often difficult to anticipate accurately, especially when relying solely on theoretical calculations. Such circumstances highlight the importance of an approach that is not solely theoretical, but also considers the actual dynamics observed in the field. The coal mining sediment pond examined in this study was initially constructed to accommodate a catchment area of 205 Ha, with a useful life of 10 years. However, the pond has reached full capacity in less than five years, 53% earlier than expected, indicating the need for re-evaluation, especially as the catchment area is planned to expand to 885 Ha. This study aims to evaluate, compare, and recalculate the sediment pond's capacity under expanded catchment conditions (885 Ha), by integrating field-based measurements and theoretical sediment yield methods to produce a more representative design. The methods employed include the Revised Universal Soil Loss Equation (RUSLE), Lane & Kalinske's Approach, Einstein's Approach, Brook's Approach, and Chang, Simons, and Richardson's Approach. RUSLE utilizes secondary data, while the other methods incorporate both primary and secondary data. The results show a wide range of sediment transport estimates, from 20,184 m^3 using Einstein's to 507,075 m^3 using Chang's. Among the evaluated methods, Lane and Kalinske, as well as Brook, produced sediment volume estimates that closely matched field-based measurements, making them suitable for field conditions. RUSLE produced a lower-bound estimate, while Einstein and Chang's method deviated significantly from the observed range. These findings underscore the importance of integrating field measurements with theoretical models to enhance the reliability of sediment-yield estimation and support informed decision-making in sediment pond.

Keywords: coal mining catchment, sediment pond performance, sediment transport modelling, suspended sediment load

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1. Introduction

A substantial proportion of mining operations, particularly coal mining, produce environmentally detrimental effluents commonly referred to as Acid Mine Drainage (AMD). These effluents are typically characterized by elevated concentrations of heavy metals and other pollutants that degrade water quality and the integrity of aquatic ecosystems integrity (Fahruddin *et al.*, 2020; Suryani *et al.*, 2022; Saptawartono *et al.*, 2024; Syam & Iryani, 2025). AMD is formed through the oxidation of sulfide minerals (most notably pyrite) when exposed to oxygen and water (Saptawartono *et al.*, 2024). The aqueous component of this reaction may derive from direct precipitation, subsurface seepage, runoff, and groundwater entering the mining area (Batubara & Saismana, 2019; Noor *et al.*, 2021; Siri *et al.*, 2022; Nugraha & Isniarno, 2022). Comprehensive analyses of mine-derived effluents have indicated elevated and spatially variable concentrations of contaminants, such as Total Suspended Solids (TSS), iron (Fe), manganese (Mn), and sulfate, underscoring the necessity for site-specific wastewater treatment interventions within mining operations (Wahyudin *et al.*, 2021; Syam & Iryani, 2025).

One of the principal mine wastewater management strategies is the implementation of dewatering systems in the form of sedimentation ponds, which are specifically designed to enable the settling of suspended solids, thereby optimizing effluent quality prior to its discharge into receiving water bodies or designated final disposal sites (Murad, 2021; Saputra *et al.*, 2023). In Indonesia, this practice is reinforced by regulatory frameworks: the Ministry of Environment and Forestry Regulation No. 5/2022 and Government Regulation No. 22/2021 mandate that mine wastewater must be treated before release to water bodies. Furthermore, the Ministerial Decree of the Ministry of Energy and Mineral Resources No. 1827 K/30/MEM/2018 on Good Mining Practice requires the development of environmental management facilities, including settling ponds, to prevent and mitigate pollution from mining operations. Nevertheless, several studies have indicated that excessive sediment accumulation can pose a significant threat to both the effective storage capacity and the operational lifespan of such facilities, with reported capacity losses ranging from 63% to complete infill relative to the original design specifications (Patro *et al.*, 2022).

This case study focuses on a sediment pond associated with coal mining operations in East Kalimantan, Indonesia, observed in 2017. The mining site is segmented into two primary operational zones: the east block, which remains actively operated, and the west block, where extraction activities are nearing completion. The sediment pond evaluated in this study is situated within the east block and was originally engineered with a storage capacity of 445,752 m^3 and an anticipated operational lifespan of 10 years. By 2017, however, a performance evaluation was considered necessary due to an expansion of the contributing catchment area from 205 Ha to 885 Ha. The evaluation indicated a marked deviation between the design lifespan and the actual operational lifespan, as evidenced by the complete infilling of sediment across all six compartments of the pond, regardless of initial projections indicating that the pond would reach maximum storage capacity only by 2022.

There are various factors that may cause the actual operational lifespan of a sediment pond to deviate from its design lifespan. One such factor is the inaccuracy in capacity estimation during the planning phase, which can lead to overly optimistic lifespan predictions that do not reflect field conditions. This underscores the need for further comprehensive research to evaluate the storage capacity and performance of sediment ponds. Previous studies have employed theoretical approaches to estimate storage capacity and sediment yield; however, these results should ideally be compiled with empirical data obtained directly from field measurements. The integration of these two approaches can provide a more accurate representation of the reliability of sediment pond design.

Previous studies have examined sediment pond performance in coal mining. Tresnawati *et al.*, (2024) evaluated TSS concentrations and deposition volumes in a multi-compartment settling pond, while Febriyanti *et al.*, (2024) analyzed treatment capacity based on rainfall-driven inflow dynamics. Putra *et al.* (2021) also assessed the carrying capacity of a settling pond using grab sampling and pollutant load carrying capacity calculations, identifying limited effectiveness across multiple sampling points. Although these studies underscore the urgency of sediment management, they primarily rely on only empirical observations and do not integrate theoretical sediment transport models. Accordingly, the present study aims to evaluate the performance of a sediment pond by employing theoretical approaches, such as Revised Universal Soil Loss Equation (RUSLE), and those proposed by Lane & Kalinske, Einstein, Brook, and Chang, alongside empirical approaches involving direct sampling at the inlet and outlet of the sediment pond, both after rainfall events and during dry conditions.

2. Materials and Method

This research was conducted as a case study on the useful life of the East Block sediment pond at a coal mining site in East Kalimantan in 2017. Both primary and secondary data were used to support the analysis, including historical rainfall data in 10-year period prior to the study. The method applied in this research was quantitative, combining empirical field measurements and theoretical approaches using the Lane & Kalinske, Einstein, Brook, and Chang equations. The sediment yield estimation in this study focuses on suspended load. The study involved the design and calculation of the sediment pond's storage capacity in response to an increase in the catchment area to 885 hectares. The result for all methods will be compared with the estimated sedimentation deposited based on primary data submitted to the laboratory, as a form of validation of the theoretical approach. The detailed flowchart is illustrated in Figure 1 below.

2.1. Study Area

The research location spans three cities/regencies: Bontang City, Kutai Kartanegara, and Kutai Timur Regency. Bontang City is located in East Kalimantan and is one of the cities that spans between 117°23′ – 117°38′ East longitude and 0°0′ – 0°2′ North latitude. The eastern part has a direct border with the Makassar Strait, while the northern and western parts directly border East Kutai Regency, and the southern boundary meets Kutai Kartanegara Regency. The research area is primarily located in Bontang Selatan Subdistrict, with a small portion extending into Kutai Kartanegara and Kutai Timur Regencies, specifically in the settlement pond area. Bontang Selatan, which is the largest area of Bontang City, covering more than 65% of Bontang's total area, followed by Bontang Utara and Bontang Barat subdistricts. Bontang city is located near the equatorial region, with monthly rainfall ranging between 150-300 mm/month, and an average annual rainfall of approximately 2,500 mm/year (BPS - Statistics of Bontang Municipality, 2022). Bontang City is predominantly covered by forest, shrubland, and mangrove, with settlement areas extending over 20 km² in the northern part. The gently sloping Bontang River flows downward into small islands and wetland areas (Widyasasi *et al.*, 2024). Meanwhile, in Kutai Kartanegara Regency, the Marang Kayu subdistrict covers an area of 866.20 km² and receives an average annual rainfall of approximately 1,800 mm/year. This subdistrict is primarily dominated by forest and plantations, with 28 km² of mining areas, and a small portion of the total area, approximately 9.41 km², serves as settlement and built-up areas. In Kutai Timur Regency, Teluk Pandan subdistrict, located on the southwestern side, has an area of 907 km², accounting for 2.96% of the total area of the regency.

This research is based on a case study of a coal mining site in East Kalimantan. At the time of the study, mining in the west block was nearly completed, while the east block was undergoing large-scale expansion. Currently, the east block remains in operation, making it the active center of mining activities in the area. The location of this research is illustrated in Figure 2.

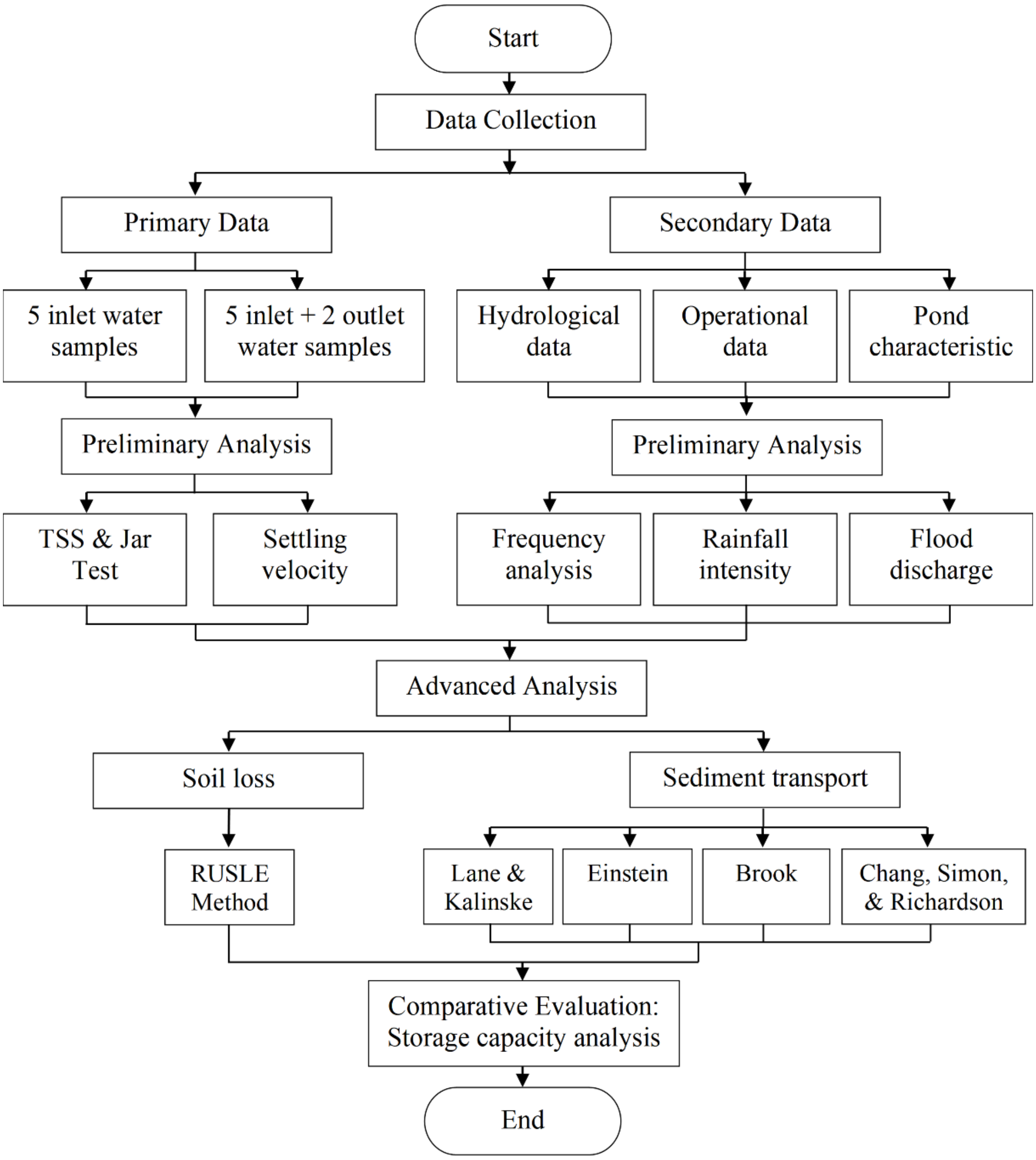

Figure 1. Framework Analysis

Following the site description, the study focuses on the sediment pond used to manage runoff and sediment transport. The catchment area of the sediment pond covers 885 hectares, consisting of four sub-catchment areas, namely waste dump pit 2AN, sump pit 2AN, pit 8AN, and pit 7B, with areas of 205 Ha, 36 Ha, 87 Ha, and 557 Ha, respectively. The existing sediment pond schematic can be illustrated in Figure 3.

2.2. Data Collection

The data used in this study consists of both primary and secondary data. Water sampling refers to SNI 6989.59:2008 on Water and Wastewater — Part 59: Method for Wastewater Sampling. The collection of sediment samples was carried out in two stages: the first was conducted during a period without rainfall, and the second was immediately after the rains. During the dry season, water sampling was limited to the inlet due to minimal or stagnant outlet flow, which was not representative for sediment analysis. The pond's outlet becomes active primarily during rainfall-induced runoff, making inlet sampling more relevant under dry conditions. Water sampling was performed at the inlet of the sediment pond, where five water samples of 500 mL each were collected.

The second stage of sampling, conducted shortly after several hours of rainfall, was carried out at both the inlet and the outlet of the sediment pond, with five water samples taken at the inlet and two water samples taken at the outlet, each of 500 mL in volume.

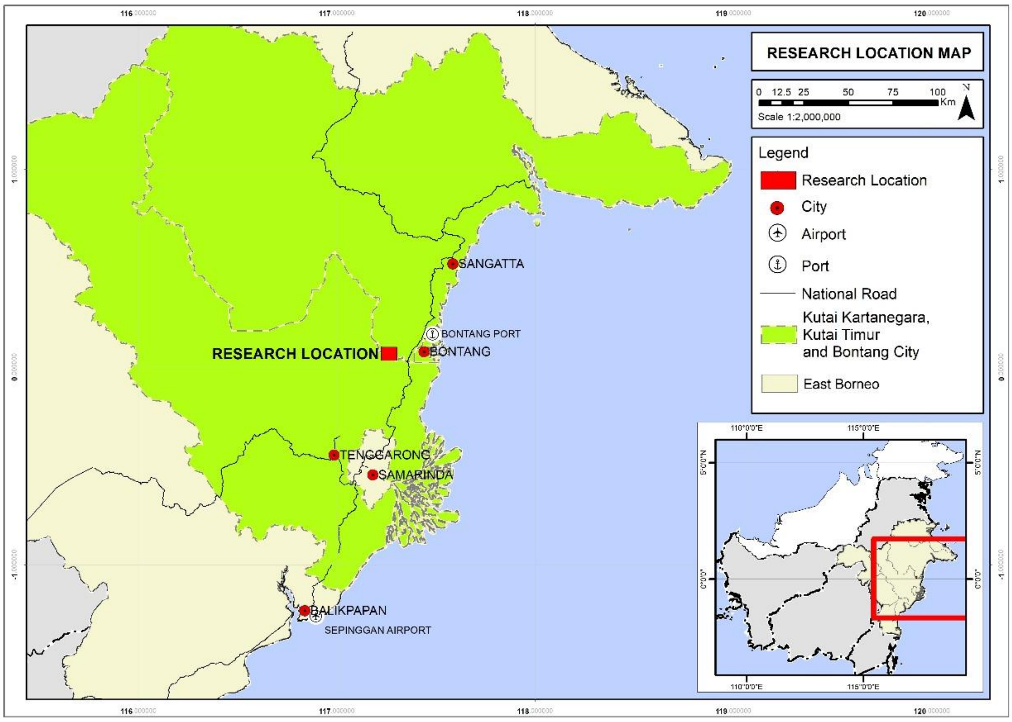

Figure 2. The research location

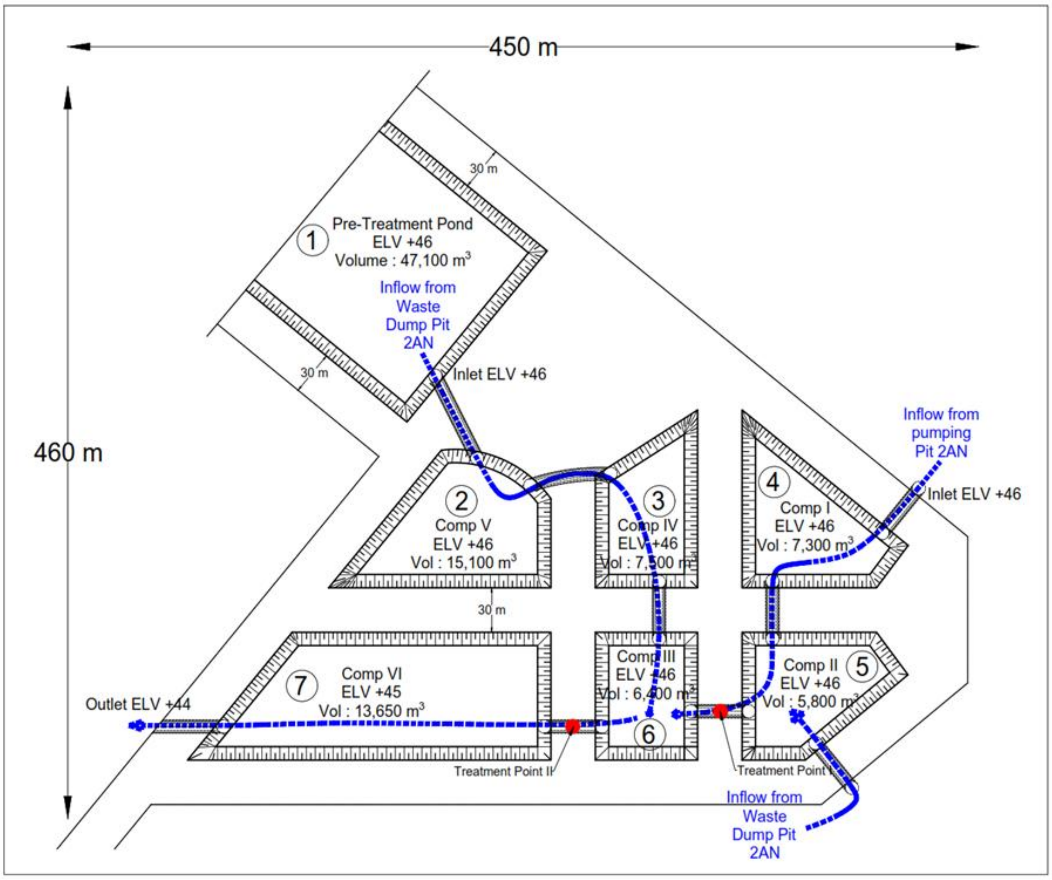

Figure 3. Existing sediment pond schematic

Total Suspended Solids (TSS) and Jar Test analyses were conducted. The TSS test was performed to determine the amount of sediment contained per liter of each sample. The Jar Test, conducted after the TSS analysis, was used to identify the appropriate coagulant dosage required to reduce the TSS concentration in the sediment pond. The TSS and jar test analyses were conducted by the on-site laboratory at the mining location.

The secondary data in this study include maps of Bontang City's administrative boundaries, site locations, and daily rainfall records for the period from 2007 to 2016. Figure 4 below illustrates the maximum daily rainfall. The highest value occurred in 2007, at around 155 mm/day. Moreover, the maximum daily rainfall remained relatively stable from 2008 to 2013. This maximum daily rainfall is analyzed to estimate design rainfall at different return periods.

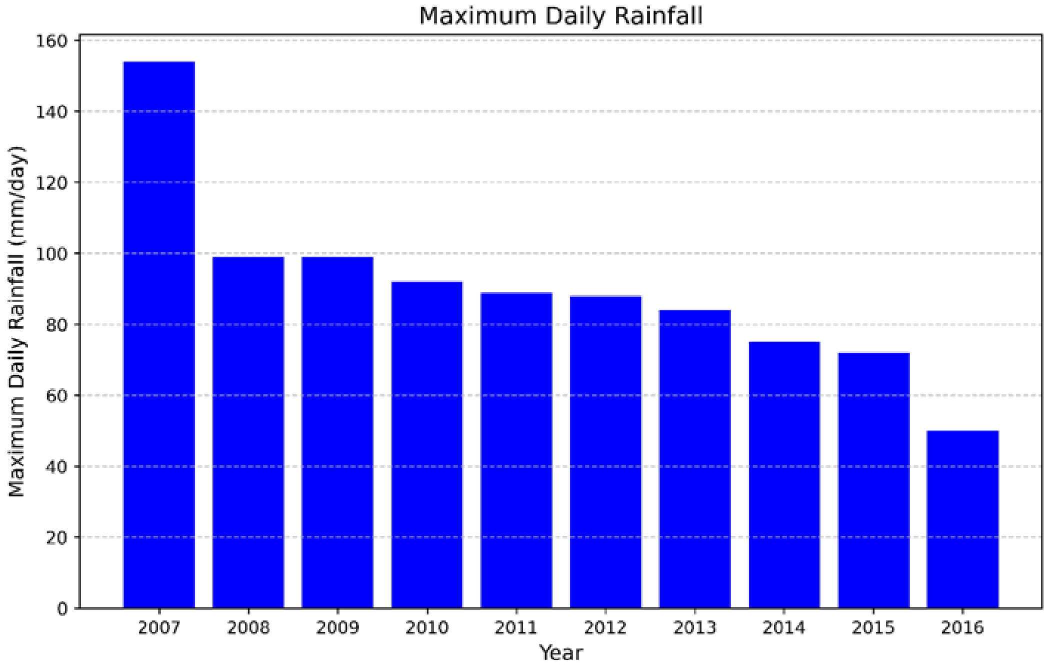

Figure 4. Maximum Daily Rainfall over 10 years

While the numerical data were accessible and sufficient for analysis, the schematic maps of the sub-catchment area's spatial visualizations limited the ability to illustrate catchment boundaries and pond placement. This limitation does not affect the validity of the calculations but should be considered when interpreting the spatial context of the results.

2.3. Design Rainfall and Flood Discharge

In this research, frequency analysis is conducted to identify the relationship between the magnitude of extreme rainfall events and their frequency of occurrence using probability distributions, which is crucial for infrastructure planning (Pudyastuti & Musthofa, 2020; Kalsum *et al.*, 2021). In the context of this research, the value of extreme events refers to the inverse relationship with occurrence probability. For instance, the high flood frequency discharge events are significantly lower than those of moderate or low discharge events. Frequency analysis can estimate the flood discharge or design rainfall for specific return periods, ranging from 1.1 years to 1,000 years, and it can also predict how often floods of a certain magnitude are likely to occur within a given time period (Ginting, 2021; Dwi *et al.*, 2024).

The design rainfall serves as one of the Inputs used to determine rainfall intensity. In this study, the rainfall intensity is calculated using the Mononobe Method. This step is crucial, as flood discharge estimation requires rainfall intensity in millimetres per hour. Through the Mononobe Method, design rainfall data with a daily temporal resolution can be converted into short-duration values (5, 10, 15 … minutes), as presented in Equation 1 (Astarini *et al.*, 2022; Triatmodjo, 2008).

$$I_t = \frac{R_{24}}{24}\left(\frac{24}{t}\right)^{\frac{2}{3}} \quad \text{....Eq.1}$$

where I_t is the rainfall intensity for a duration t (mm/h), R_{24} is the maximum 24-hour rainfall (mm), while t is the duration of rain (hours).

In addition, two other parameters are considered in calculating flood discharge using the Ration Method: *A* (the catchment area) and *C* (the runoff coefficient). The catchment area is determined based on the watershed area under study or the area being considered for analysis.

After all necessary parameters for the Rational Method are determined, the flood discharge can be calculated using the Rational Method equation, as presented in Equation 2 (Sari & Irawan, 2021; Triatmodjo, 2008).

$$Q = 0.278 \times C \times I \times A \quad \text{....Eq.2}$$

where Q is the peak discharge resulting from rainfall with a certain intensity, duration, and frequency (m^3/s), C is the runoff coefficient determined by land cover (dimensionless), I is the hourly rainfall intensity (mm/h), and A is the catchment area (km2).

2.4. Soil Loss by RUSLE Method

The Revised Universal Soil Loss Equation (RUSLE) is one of the methods used to predict the magnitude of erosion or the long-term average annual soil loss caused by rainfall-induced runoff on a given slope (Cantik *et al.*, 2023). The calculation of soil loss using the RUSLE Method is presented in Equation 3.

$$A = Ri \times K \times LS \times C \times P \quad \text{....Eq.3}$$

where *A* represents the average annual soil loss (t/ha/y), *Ri* denotes the rainfall erosivity factor (MJmm/ha/h/y), *K* is the soil erodibility factor (t/ha/h/ha/MJ/mm), *LS* refers to the slop length and steepness factor (dimensionless), *C* is the cover management factor (dimensionless), and *P* represents the support practice factor (dimensionless) (Cantik *et al.*, 2023; Hadi *et al.*, 2023). The calculation of rainfall erosivity is shown in Equation 4 below.

$$Ri = \sum_{i=1}^{12} 1.735 \times 10\left(1.5\log_{10}\left(\frac{P_i^2}{P}\right) - 0.08188\right) \quad \text{....Eq.4}$$

where *Ri* represents the rainfall erosivity factor (MJmm/ha/h/y), *Pi* denotes the monthly rainfall (mm), and *P* refers to the annual rainfall (mm).

The next parameter is the soil erodibility factor. This factor reflects the soil's resistance to rainfall and surface runoff (Hanifa & Suwardi, 2022) and is determined by soil characteristics such as structure, texture, permeability, and organic matter content (Hanafi & Pamungkas, 2021a; Hanifa & Suwardi, 2022). Another essential parameter to be determined is the slope length and steepness factor (LS), which plays a critical role in the RUSLE model. LS directly influences the rate of erosion and the volume of surface runoff (Hanafi & Pamungkas, 2021b; Pramasela *et al.*, 2022; Faisol *et al.*, 2024).

The following parameter to be determined is the cover management factor (C), which reflects the influence of land cover type on the rate of erosion (Virlayani *et al.*, 2024). A lower C value indicates better land cover performance in reducing erosion, and vice versa. The support practice factor (P) in the RUSLE method represents the effectiveness of soil conservation practices in reducing erosion rates through surface runoff and infiltration management (Sianipar *et al.*, 2023). Compared to the C factor, which focuses on what covers the soil, the P factor emphasizes how the soil is physically managed to resist erosion (Kebede *et al.*, 2021). P values range from 0 to 1, where lower values indicate more effective conservation practices in minimizing erosion (Akbar, 2021; Hanafi & Pamungkas, 2021b; Cantik *et al.*, 2023).

2.5. Settling Velocity Based on Stokes-Newton Law

In the design planning of sedimentation ponds, one of the key parameters that must be analyzed in advance is the particle settling velocity. Several factors influence this velocity, including particle size, fluid type, and viscosity (Omland *et al.*, 2005; Astuti, 2020; Putri *et al.*, 2024). The calculation of particle settling velocity can be performed analytically based on the physical laws of fluid flow and particle motion within a fluid. For small particles (diameter < 0.1 mm) moving in laminar flow conditions (Reynolds number Re < 1), the settling velocity can be determined using the Stokes–Newton equation (Isnaeni, 2021; Wahyudin *et al.*, 2021) as presented in Equation 5 below.

$$\upsilon_s = \frac{g \times {D_s}^2 \times (\rho_s - \rho)}{18 \times \mu} \quad \text{....Eq.2}$$

where υ_s is the particle settling velocity (m/s), g is the gravitational acceleration (m/s^2), D_S is the diameter of the particle (m), ρ_s is the particle density (kg/m^3), ρ is the fluid density (kg/m3), μ is the fluid viscosity (m^2/s). (Lane & Kalinske 1941; Brooks 1963; Chang *et al.* 1965, as cited in Yang 1996)

2.6. Sediment Yield Methods

The sediment transport rate for the sediment pond was calculated using several analytical approaches as a comparative assessment to the RUSLE method in predicting the pond's storage capacity under a projected catchment area of 885 hectares. The approaches employed in this study include those proposed by Lane and Kalinske, Einstein, Brook, and Chang, Simon, and Richardson. The key differences among these methods in terms of formulation, parameter sensitivity, and theoretical characteristics can be seen in Table 5.

Table 5. Comparative Overview of Sediment Yield Methods

No.	Method	Equation		Sensitivity Parameter	Characteristic
1.	Lane and Kalinske	$q_{sw} = q \times C_a \times P_L \times \exp\left(\frac{15 \times \omega \times a}{U_* \times D}\right)$ $U_* = (g \times D \times S)^{\frac{1}{2}}$	(12) (13)	Flow velocity, particle size, and flow depth	For open channels, integrates hydraulic and particle properties
2.	Einstein	$q_{sw} = 11.6 \times U_* \times C_a \times a \times \left\{\left[2.303 \log \frac{30.2 \times D}{\Delta}\right] I_1 + I_2\right\}$	(14)	Velocity and particle size distribution	Based on velocity-concentration, includes turbulence and lift forces
4.	Brook	$q_{sw} = \frac{q_{sw}}{qC_{md}} \times q \times \gamma \times C_{md}$	(15)	Discharge and sediment concentration	Uses discharge ratio, suitable for design with limited data
5.	Chang. Simon, & Richardson	$q_{sw} = \gamma \times D \times C_a \times \left(VI_1 - \frac{2U_*}{k} I_2\right)$	(16)	Flow geometry and flow velocity	Semi-theoretical, integrates depth and velocity-concentration distribution

Description:
qsw = suspended sediment transport rate (lb/s)
q = total flow discharge per unit width (ft3/s)/ft
Ca = sediment concentration by dry weight (lb/ft3)
PL= flow path coefficient (dimensionless)
ω = settling velocity (in/s)
a = settling height (in, Lane and Kalinske)
a = settling height (ft, Einstein)
U* = horizontal flow velocity (in/s, Lane and Kalinske)
U* = horizontal flow velocity (ft/s, Einstein and Chang)
D = flow depth (in, Lane and Kalinske)
D = flow depth (ft, Einstein and Chang)
Δ = sediment particle characteristic (ft)
I_1 and I_2 = integrals of sediment concentration and flow velocity distribution with respect to flow depth (dimensionless)
qCmd = reference discharge used during sediment concentration measurement (lb/s)/ft
γ = specific weight of water (lb/ft3)
Cmd = dissolved sediment concentration (lb/ft3)
V = low velocity (ft/s)
k = empirical calibration constant (dimensionless)

3. Result and Discussion

3.1. Design Rainfall and Flood Discharge

The frequency analysis conducted in this study processes daily maximum rainfall data recorded over ten years period, from 2007 to 2016. Probability plotting is adjusted according to the number of rainfall data available, after which the calculations of mean, standard deviation, skewness coefficient, and kurtosis coefficient are performed. The statistical parameters calculations of the Frequency Analysis are presented in Table 5 below.

Table 5. Statistical Parameters

No.	Probability (m/(N+1))	Year	Rainfall (mm)
1	0.091	2007	154.00
2	0.182	2008	99.00
3	0.273	2009	99.00
4	0.364	2010	92.00
5	0.455	2011	89.00
6	0.545	2012	88.00
7	0.636	2013	84.00
8	0.727	2014	75.00
9	0.818	2015	72.00
10	0.909	2016	50.11
		The number of data:	10
		Mean:	90.21
		Standard Deviation (S_D):	26.76
		Coeff. Skewness (C_S):	1.35
		Coeff. Kurtosis (C_k):	3.89

Following the calculation of statistical parameters, the rainfall data were evaluated using the Chi-Square Test and the Smirnov-Kolmogorov Test. In the Chi-Square Test, all distributions, including Normal, Log-Normal, Gumbel, and Log-Pearson III, were accepted. Similar results were obtained from the Smirnov-Kolmogorov Test, where all distributions were also accepted. However, according to the Chi-Square Test, the best-fitting distribution was Log-Pearson III, while the Smirnov-Kolmogorov Test indicated Log-Normal as the best fit. Between the two, the higher XT value was selected, which corresponded to the Log-Pearson III distribution. The results of the design rainfall are presented in Table 6. After the Frequency Analysis was carried out, the next step was to calculate the rainfall intensity using the Mononobe method. The results of this calculation are shown in Table 7.

Based on Table 7, the rainfall intensity applied in the Rational Method for flood discharge calculation is taken at a 60-minute duration and a 25-year return period, resulting in 49.978 mm/h. In addition to rainfall intensity, the runoff coefficient is set at 0.3 (undeveloped area). Once all discharge parameters are defined, the flood discharge can be calculated for each catchment area, with detailed results presented in Table 8.

Table 6. Design Rainfall

Probability	Return Period (year)	Design Rainfall (mm)
50%	2	86.614
20%	5	110.314
10%	10	125.463
4%	25	144.163
2%	50	157.850
1%	100	171.377
0%	1000	216.482

Table 7. Rainfall Intensity

Duration (mins)	Return Period (year)						
	2	5	10	25	50	100	1,000
20	62.460	79.550	90.474	103.959	113.829	123.584	156.110
45	36.376	46.329	52.691	60.545	66.293	71.974	90.917
60	30.027	38.244	43.495	49.978	54.723	59.413	75.050
120	18.916	24.092	27.400	31.484	34.474	37.428	47.279

Table 8. Flood Discharge for Each Sub-catchment Area

Sub Catchment Area	A (Ha)	Q (m^3/s)
Waste Dump Pit 2AN	205	8.545
Sump Pit 2AN	36	1.501
Pit 8AN	87	3.626
Pit 7B	557	23.217
Total	**885**	**36.889**

Based on Table 8, the flood discharge for the sediment pond, calculated using the updated catchment area of 885 Ha, is 36.889 m3/s. This flood discharge value is then specifically used as input data in the RUSLE equation and in sediment transport calculations using various analytical approaches. This value represents the actual hydrological condition of the sediment pond's revised catchment area. By incorporating flood discharge based on actual data, the sediment pond design can be calculated more responsively to the potential runoff and sediment load carried during the annual period.

3.2. RUSLE for Soil Loss

Soil loss estimation using the RUSLE method begins with calculating the rainfall erosivity factor, Ri. The value of Ri is derived using Equation 10, which serves as the basis for quantifying rainfall erosivity. The calculated value of Ri from 2008 to 2016 is illustrated in Figure 6 below.

Based on Figure 6, the average annual rainfall erosivity value is 298.161 MJmm/ha/h/y. This value is subsequently used as input in the RUSLE calculation, as RUSLE is specifically designed to estimate annual soil loss. The use of a sufficiently long data period ensures that the results are representative of local climatic conditions and helps to reduce the influence of extreme annual outliers. Following the determination of rainfall erosivity, the LS, C, and P factors are identified by referring to Table 2 – Table 4. The final results of RUSLE-based soil loss estimation are presented in Table 9.

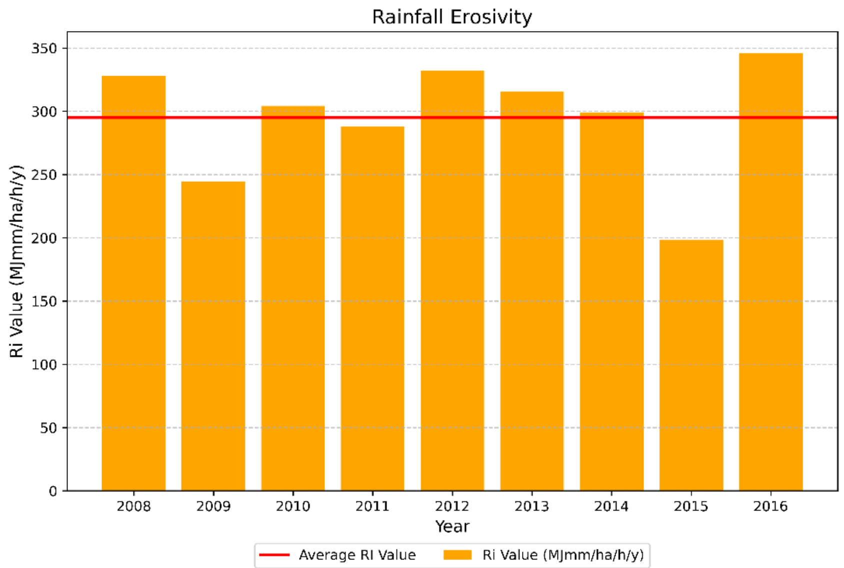

Figure 6. Rainfall erosivity values, Ri

Table 9. Result of RUSLE's Soil Loss

No.	Parameter	Unit	Value	Remarks
1.	Rainfall erosivity (Ri)	MJmm/ha/h/y	298.161	Average rainfall erosivity
2.	Soil erodibility factor (K)	-	0.296	Gray regosol (young, loose soil, commonly found in mining areas)
3.	Slope length and slope steepness factor (LS)	-	1.4	Slope Gradient: 10%
4.	Cover management factor (C)	-	1	Cultivated bare land
5.	Support practice factor (P)	-	1	No conservation practices
	Soil loss by RUSLE (A)	**t/ha/y**	**123.558**	Catchment area of 885 Ha
	Soil loss by RUSLE (A)	**t/y**	**109,349**	

3.3. Settling Velocity by Stokes-Newton Law

The settling velocity of sediment particles in the sediment pond is calculated using the Stokes–Newton Law, as outlined in Equation 11. All parameters required for the settling velocity calculation were obtained directly from laboratory testing of primary data samples, with the exception of the gravitational acceleration value, which is a standardized value. The detailed values used in the calculation are presented in Table 10 below.

Based on the calculations in Table 10, the settling velocity derived from the Stokes–Newton Law is 0.660 m/s or 25.979 in/s. This relatively high settling rate indicates that sediment particles tend to settle quickly under calm flow conditions. Such behaviour supports the effectiveness of the existing sediment pond in facilitating sediment separation.

Table 10. Parameters for settling velocity using Stokes-Newton Law

No.	Parameter Persamaan	Unit	Nilai	Source
1.	Gravitational acceleration (g)	m/s^2	9.81	Standard constant
2.	Particle diameter (Ds)	m	$4x10^{-5}$	
3.	Particle density (ρ_s)	kg/m^3	1,939	Primary sample lab.
4.	Fluid density (ρ)	kg/m^3	1,180	results
5.	Fluid viscosity (μ)	m^2/s	$1,003x10^{-6}$	
6.	Settling velocity (υ_s)*	m/s	0.660	Stokes-Newton Law

3.4. Suspended Load Calculation Using Sediment Yield Method

Four analytical approaches were used to estimate suspended sediment load: Lane & Kalinske's Approach, Einstein's Approach, Brook's Approach, and Chang, Simons, and Richardson's Approach. Each method requires a specific set of input parameters to perform the calculation accurately. These parameters include hydraulic characteristics, sediment concentration, flow depth, particle properties, and empirical coefficients. The required parameters for each method are summarized in Table 11.

Based on Figure 7, notable differences are observed in the suspended sediment transport rate (q_{sw}) among the various analytical approaches, indicating that each method exhibits distinct sensitivities to hydraulic parameters and sediment characteristics. The calculation using Einstein's equation yields the lowest sediment transport rate at 0.021 lb/s/ft, reflecting a theoretical approach based on the vertical distribution of velocity and sediment concentration. This method is suitable for controlled flow conditions and very fine particles, but is considered too conservative for sediment pond design in mining areas with high sediment loads.

In contrast, the Brook and Chang, Simons, and Richardson methods produce higher and relatively comparable sediment transport rates (0.433 lb/s/ft and 0.537 lb/s/ft, respectively). Brook's method relies on the ratio of qsw/qcmd and flow velocity correction, while Chang's method incorporates vertical distribution integrals, I_1 and I_2, with a more aggressive correction graph than Einstein's. Both results are deemed suitable for representing dynamic field conditions.

The results of these calculations, along with a comparative analysis of suspended sediment load values across the four methods, are presented in Figure 7. The Lane & Kalinske approach yields a moderate value of 0.245 lb/s/ft, incorporating flow path and sedimentation efficiency through an exponential expression. This method is appropriate when flow discharge and sediment concentration data are well-defined.

Table 11. Parameter Used

No.	Parameter	Unit	Value
1.	Flow discharge per unit width (q)	$(m^3/s)/m$ $(ft^3/s)/ft$	1.230 13.236
2.	Flow depth (R=R'=D)	m in	4 157.48
3.	Sediment concentration (Ca)	lb/ft^3	6.675×10^{-4}
4.	Gravitational acceleration (g)	m/s^2 in/s^2	9.81 386.22
5.	Sediment particle size (d65)	in	0.0236
6.	Settling velocity (υ_s)	m/s in/s	0.660 25.979
7.	Settling height (a)	m in	0.271 10.512
8.	Channel slope (S)	-	0.067
9.	Viscosity (μ)	m^2/s in^2/s	$1{,}003 \times 10^{-6}$ $1{,}555 \times 10^{-3}$
10.	Water density (ρ)	kg/m^3 lb/ft^3	1,180 73.667

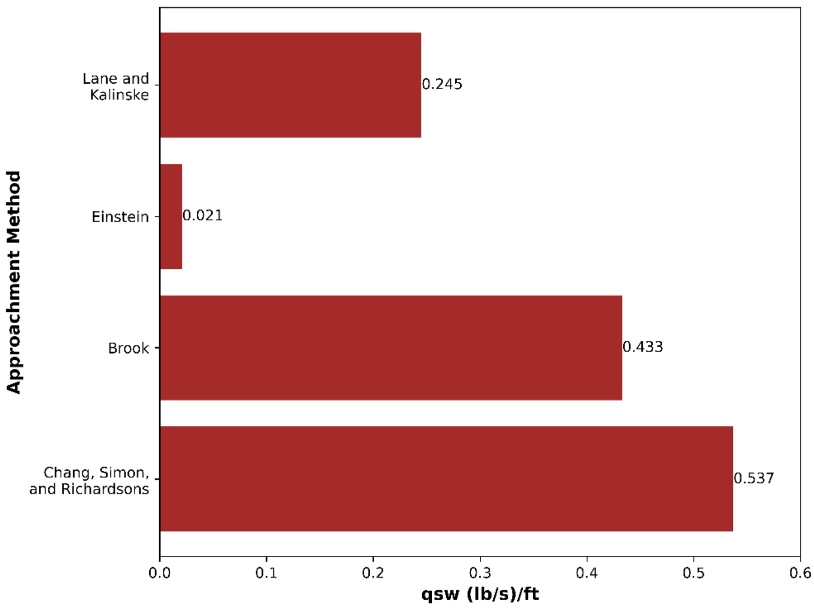

Figure 7. Comparison of suspended load results

3.1 Sediment Pond Design Plan

The sediment pond design plan is calculated based on the total flood discharge and sediment transport values obtained in the previous subsections. This design is derived from the estimated sedimentation that may occur in the pond using five methods: RUSLE, Lane & Kalinske's Approach, Einstein's Approach, Brook's Approach, and Chang, Simons, and Richardson's Approach. The design results for each method are presented in Table 12.

Table 12 presents the result of annual sediment deposition calculated using several methods. Based on the sediment yield's method, annual sediment deposition ranges from 20,184 to 507,075 m^3/year. Pond dimensions were derived by converting daily sediment load into annual volume, then applying a safety factor of 1.3 to ensure adequate capacity under fluctuating sediment loads.

Table 12. Comparison of sediment pond volume results

No.	Sediment deposition (m^3/year)		Pond dimensions (m^3)		
	Method	**Results**	**P (m)**	**L (m)**	**d (m)**
1	RUSLE	192,063.36	353.33	176.66	4
2	Lane and Kalinske	231,076.18	339.91	169.95	4
3	Einstein	20,183.93	100.46	50.23	4
4	Brook	408,842.15	452.13	226.06	4
5	Chang, Simon, Richardson	507,075.25	503.53	251.76	4

To validate the theoretical calculations, a comparative analysis was conducted using primary data collected from inlet and outlet measurements under existing conditions. The samples were tested in the laboratory for TSS concentration and sedimentation behavior under still water conditions. Based on the test, it was observed that 1.11% to 3.33% of the total water volume settled as sludge, where the lower percentage was observed in samples collected during dry conditions, and the upper bound followed rainfall events. Accordingly, the estimated annual sediment volume ranged from 208,000 m^3/year to 416,100 m^3/year.

When compared to the theoretical calculations presented in Table 12, the estimated annual sediment volume based on laboratory testing (208,000 to 416,100 m^3/year) indicates that the Lane and Kalinske as well as the Brook Methods fall within a relevant range and can be considered a representative approach for field conditions. The RUSLE Method yields a value that is relatively close to the lower bound. In contrast, the Einstein Method produces an estimate significantly below the minimum threshold, while the Chang, Simon, and Richardson exceed the upper bound. Therefore, both require further evaluation regarding the suitability of their parameters and underlying assumptions.

Overall, the result patterns indicate that empirical methods can serve as a baseline, provided that the parameters used are derived from primary data collected and tested directly in the field. Method selection should be further adjusted based on site-specific characteristics, design objectives, and the acceptable level of long-term sedimentation risk.

3.2 Sediment Pond Maintenance Strategies

The variation in estimates of sediment volumes across methods, as shown in Table 12, directly influences the scale and frequency of maintenance required. For instance, methods such as Chang and Brook suggest significantly larger sediment accumulation, which would demand more frequent dredging and larger pond dimensions, while lower estimates may risk underdesign. Therefore, maintenance strategies should be responsive to both theoretical projection and observed field conditions. Several maintenance options can be implemented for the sediment pond, including:

1. Routine Inspection and Monitoring Protocols
   Routine inspection is a cornerstone of sediment pond maintenance in coal mining operations. Regular inspections, especially after heavy rainfall, are essential to assess sediment accumulation, structural integrity, and water quality (Kathuria *et al.*, 1976; Parker & Dumaresq, 2002; Drake & Guo, 2008).
2. Preventive Measures to Minimize Sediment Inflow
   Preventive strategies upstream of sediment ponds can significantly reduce maintenance demands. These include soil stabilization through revegetation, mulching, and erosion control blankets, as well as the installation of check dams and diversion ditches. In Indonesia, best practices for erosion protection during mine development emphasize proactive planning based on hydrological and soil assessments (Sloat & Redden, 2005).
3. Revegetation and Reclamation of Mining Areas
   Revegetation and reclamation are long-term strategies that support sediment

control and ecological restoration. In Indonesia, revegetation practices are guided by forestry science and legal frameworks, with mining companies selecting appropriate plant species to stabilize soil and restore biodiversity. Reclamation efforts typically involve returning topsoil, adding organic matter, and planting fast-growing cover crops (Pambudi *et al*., 2023).

4. Conclusion

The conclusion addressing the objective of this study is that integrating primary and secondary data in formulating the capacity and design of sediment ponds is essential for a representative performance evaluation. This is evident from the significant differences between the RUSLE results and those of sediment yield calculations. Furthermore, the comparison among analytical approaches reveals that sensitivity to field parameters greatly influences the estimation of pond capacity and lifespan. By validating sediment behavior under both dry and post-rainfall conditions, the study demonstrates the value of empirical data in refining theoretical estimates. Future research should focus on dynamic modeling, long-term sedimentation risks, and maintenance strategies to support adaptive and informed decision-making. Through this approach, this study contributes an integrated empirical-theoretical framework applicable to tropical mining environments

Funding Agencies

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Data availability statement

All data utilized in this study were derived from a real-world case and actual operational activities, obtained directly through field sampling, observation, and technical documentation. However, in accordance with the request of the involved parties, the identity of the institution is not disclosed in this publication to preserve confidentiality and uphold ethical standards of collaboration. Nevertheless, the data used are valid, verified, and available for methodological evaluation within the context of the study.

Author Contributions

BK served as the lead author, conducting field data collection, conceptualizing the overall structure of the manuscript, and drafting the paper. **EG** contributed to hydrological calculations, supervised the analytical process, and assisted in manuscript preparation. **RP** supported the empirical sediment transport analysis, evaluated the computational results, and participated in writing the paper. **BM & JK** provided input on sediment pond maintenance strategies and contributed to the manuscript development.

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