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The Role of Riparian Vegetation in Pollutant Filtration and Sediment Stabilization in Lake Tondano, Indonesia

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Abstract: *Riparian vegetation plays a crucial role in maintaining aquatic ecosystem stability by acting as a natural buffer against anthropogenic pollution and erosion. This study analyzed the composition, structure, and ecological functions of riparian vegetation in Lake Tondano, North Sulawesi, Indonesia, with emphasis on pollutant filtration and sediment stabilization. Field surveys were conducted from May to August 2025 at ten riparian stations surrounding Lake Tondano (4,638 ha). Vegetation sampling used a stratified line transect method with fifty plots of varying sizes according to vegetation strata. Quantitative analysis included relative abundance, frequency, dominance, Importance Value Index (IVI), and the Shannon–Wiener diversity index (H'). Ecological functions were assessed through correlations between vegetation structure and reported nutrient and sediment reduction efficiencies from tropical riparian studies. A total of fifteen dominant riparian species were identified, mainly from the families Poaceae and Cyperaceae. Cyperus papyrus (IVI = 21.81%) and Metroxylon sagu (IVI = 29.65%) functioned as key ecological species, while Ficus septica showed the highest IVI (90.83%), indicating strong structural dominance. The Shannon–Wiener diversity index (H' = 2.65) reflects moderate to high diversity. Riparian vegetation was estimated to reduce nutrient loads by 40–60% and erosion by 30–50%, highlighting its importance for ecosystem-based lake management.*

Keywords: *Ecosystem restoration, Eutrophication, Lake Tondano, Riparian vegetation, Sediment stabilization.*

1. INTRODUCTION

Lakes are vital inland water ecosystems that provide essential services such as freshwater supply, fisheries, energy production, irrigation, and recreation. The sustainability of these services is strongly influenced by the condition of riparian zones, which form transitional areas between terrestrial and aquatic ecosystems. Riparian vegetation functions as a natural buffer that filters pollutants, stabilizes sediments, regulates nutrient cycles, and maintains water quality (Luke *et al.*, 2018). When riparian zones are degraded, surface runoff increases, sediments and nutrients enter lakes more easily, and eutrophication and shoreline erosion become more severe problems (Marconato *et al*., 2015). In many tropical regions, including Indonesia, rapid land-use change has caused widespread degradation of riparian ecosystems. Agricultural expansion, settlement growth, and tourism development have reduced natural buffer zones around rivers and lakes, weakening their ecological functions (Wilts *et al.*, 2023). As a result, many lakes experience increasing nutrient pollution, sedimentation, and declining ecological quality. Several studies have shown that loss of riparian vegetation

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significantly increases nitrogen and phosphorus loading, turbidity, and erosion in freshwater systems (Londa *et al.*, 2025; Rotinsulu *et al.*, 2018; Kadir *et al.*, 2019; Mayer *et al.*, 2007).

In Indonesia, many studies have shown that riparian and riverside vegetation plays a critical role in erosion control, flood mitigation, and water conservation. Research in Bengkulu revealed that tree diversity along riversides contributes significantly to disaster mitigation through soil binding and water absorption (Gustari *et al.*, 2023). Similar results were reported in Sulawesi, where *Ficus* species were found to have strong soil-binding capacity due to their extensive root systems (Siappa *et al.*, 2016; Zaharah *et al.*, 2016). In eastern Indonesia, tree diversity was also proven to support water conservation and infiltration in rural landscapes (Rudin *et al.*, 2020; Aziz *et al.*, 2020). These findings indicate that vegetation structure strongly determines the ecological stability of riparian and riverside ecosystems.

Lake Tondano in North Sulawesi, Indonesia, covers about 4,638 ha and is an important source of water for irrigation, fisheries, hydropower, and tourism. However, population growth and agricultural intensification around the lake have increased nutrient and sediment inputs through more than thirty inlet rivers. This has caused eutrophication, high turbidity, and rapid sediment accumulation, threatening the ecological and economic functions of the lake (Warouw *et al.*, 2022; Hendratta *et al.*, 2024a; Zaharah *et al.*, 2016). Despite these problems, management efforts have mostly focused on water quality monitoring and pollution control, while the role of riparian vegetation as a natural solution has received limited attention. Previous studies around Lake Tondano mainly emphasized limnological characteristics and water chemistry (Londa *et al.*, 2025; Zaharah *et al.*, 2016), while research on riparian vegetation has been very limited. In contrast, studies in other regions of Indonesia demonstrate that vegetation structure is strongly linked to erosion control and hydrological stability (Gustari *et al.*, 2023; Siappa *et al.*, 2016; Rudin *et al.*, 2020).

However, similar integrated studies linking riparian vegetation structure with ecological function have not yet been comprehensively conducted in Lake Tondano. Therefore, the novelty of this study lies in its integrated analysis of riparian vegetation composition, structure, and ecological function in Lake Tondano, focusing specifically on its role in pollutant filtration and sediment stabilization. Unlike previous studies that examined only water quality or only vegetation, this research combines vegetation structure analysis with functional evaluation to explain how dominant species contribute to nutrient and sediment reduction. This study aims to analyze the composition and structure of riparian vegetation in Lake Tondano and to evaluate its ecological functions in filtering pollutants and stabilizing sediments. The results are expected to provide a scientific basis for riparian conservation and restoration as a nature-based solution for controlling eutrophication and sedimentation in Lake Tondano.

2. RESEARCH METHOD

Study Area

The study was conducted between May and August 2025 around Lake Tondano (1°13′38.27″ N, 124°53′18.45″ E). Ten sampling stations were established along riparian zones with varying land-use conditions (Figure 1).

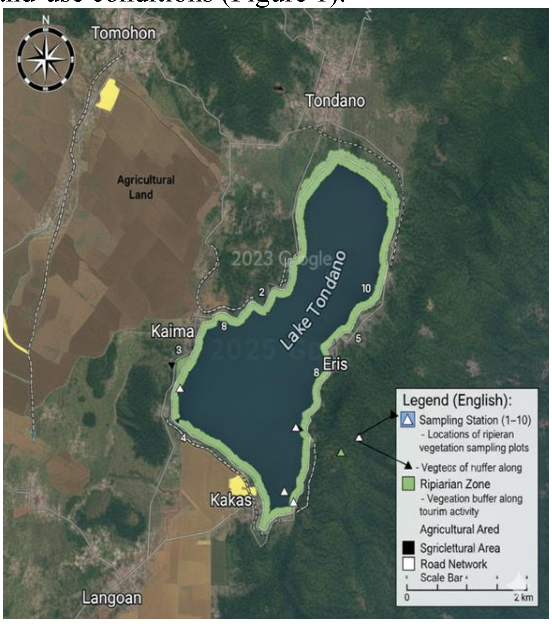

Figure 1. Map of Lake Tondano and Locations of Riparian Sampling Stations

Sampling and Data Collection

Sampling employed a **stratified line-transect method** with a total of 50 plots distributed across the stations. Plot sizes were

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adjusted by vegetation strata: 1×1 m (herbs), 2×2 m (seedlings), 5×5 m (saplings), 10×10 m (poles), and 20×20 m (trees) (Vermeersch *et al*., 2016). Vegetation abundance, frequency, and dominance were recorded for each species. Field equipment included measuring tapes, ropes, wooden stakes, and field identification guides. Species identification was verified using regional floras and standard taxonomic references, and uncertain specimens were re-examined after fieldwork. To ensure data accuracy, duplicate records were cross-checked among observers to reduce recording errors and improve data consistency.

Data Analysis

Quantitative parameters followed standard ecological equations:

a. Abundance and type

$$K = \frac{Number\ of\ individual\ of\ a\ species}{Number\ of\ trap} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

b. Relative Abudance

$$KR = \frac{Number\ of\ individual\ of\ a\ type}{Total\ number\ of\ individuals\ of\ all\ types} x100\% \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

c. Relative Frequency,

$$FR = \frac{Frequency\ of\ a\ type}{Frequency\ of\ all\ plots} x100\% \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

d. Dominance

$$D = \frac{Area\ of\ sample\ plot}{Area\ of\ all\ plot} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

e. Relative Dominance

$$DR = \frac{Dominance\ of\ a\ type}{Dominance\ of\ a\ plot} x100\% \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

f. Important Value Index (IVI)

$$IVI = KR + FR \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

g. Diversity Index

$$H' = -\sum_{i=1}^{s} p_i \ln p_i \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

Ecological functions were evaluated using correlations between IVI and reported nutrient or sediment reduction efficiency from tropical riparian literature (Mayer *et al*., 2007; Mello *et al*., 2017).

3. RESULTS AND DISCUSSION

Vegetation Composition and Structure

A total of 15 dominant riparian plant species were recorded around Lake Tondano, representing 11 families and 8 orders. The most represented families were Poaceae (6 species) and Cyperaceae (2 species), indicating that many species present are adapted to semi-aquatic and periodically flooded environments. Similar dominance of grasses and sedges has been observed in other wetland and riparian ecosystems in Indonesia, especially in areas with fluctuating water levels and soft, nutrient-rich substrates (Aziz *et al*., 2020; Kadir & Bahagia, 2019). In this study, herbaceous and grass species accounted for about 70% of all recorded individuals, while woody species occurred in lower numbers and mainly contributed to vertical structure. These patterns suggest that the riparian vegetation is largely composed of disturbance-tolerant species, which may be related to land-use activities around the lake (Hendratta *et al*., 2024a).

Cyperus papyrus showed the highest number of individuals (63), followed by *Urochloa mutica* (61), whereas *Diplazium esculentum* had the lowest abundance (19) (Table 1). This distribution indicates that the riparian zone is dominated by species that are able to grow well in wet and unstable substrates. Such species are often reported to play a role in sediment retention and nutrient uptake because of their dense root systems and high growth rates, although this study did not directly measure these processes (Mayer *et al*., 2007; Mello *et al*., 2017). Considering that

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Lake Tondano receives substantial nutrient and sediment input from surrounding human activities (Londa *et al*., 2025), the dominance of these species is consistent with environmental conditions that favor flood-tolerant pioneer vegetation.

Table 1. Composition of Riparian Vegetation in Lake Tondano

No	Species	Family	Ordo	Total
1	*Leersia hexandra* Sw	Poaceae	Poales	57
2	*Colocasia esculenta*	Araceae	Alismatales	41
3	*Ipomoea aquatica*	Convolvulaceae	Solanales	33
4	*Cyperus platystylis*	Cyperaceae	Poales	38
5	*Vigna luteola*	Fabaceae	Fabales	29
6	*Urochloa mutica* (Forssk.) T.Q. Nguyen	Poaceae	Poales	61
7	*Dinebra chinensis* (L.)	Poaceae	Poales	42
8	*Ischaemum latifolium* (Spreng.) Kunth	Poaceae	Poales	45
9	*Ficus septica*	Moraceae	Rosales	47
10	*Phragmites australis* (Cav.) Trin. ex Steud.	Poaceae	Poales	30
11	*Acrostichum aureum* L.	Pteridaceae	Polypodiales	26
12	*Cyperus papyrus*	Cyperaceae	Poales	63
13	*Metroxylon sagu*	Arecaceae	Arecales	28
14	*Ludwigia octovalvis*	Onagraceae	Myrtales	22
15	*Diplazium esculentum* (Retz.) Sw.	Arthyriaceae	Polypodiales	19

The occurrence of species from Araceae (*Colocasia esculenta*), Arecaceae (*Metroxylon sagu*), and Moraceae (*Ficus septica*) indicates that the riparian vegetation still includes different growth forms, from ground cover to taller woody plants (Table 1). This layered structure may contribute to greater habitat complexity and soil protection, as reported in other Indonesian riparian and riverside ecosystems (Rudin *et al*., 2020; Gustari *et al*., 2023). *Ficus* species, in particular, are known to have extensive root systems that can bind soil in riverbank environments (Siappa *et al*., 2016; Zaharah *et al*., 2016), but in this study their role is inferred from structure and abundance data rather than from direct measurements of erosion control.

Ferns such as *Acrostichum aureum* and *Diplazium esculentum* were also recorded (Table 1), indicating moist substrate conditions that support fern growth. Their presence suggests that some riparian sections still provide suitable microhabitats for continuous vegetative regeneration. However, changes in land cover in the Tondano watershed between 2002 and 2015, especially the conversion of forest to agriculture and built-up areas, have increased runoff and sediment delivery to the lake (Rotinsulu *et al*., 2018). This broader landscape change may partly explain why flood-tolerant and fast-growing species dominate the current riparian vegetation.

Overall, the dominance of the order Poales (8 species, 55%) reflects specialization under fluctuating hydrological conditions. Similar vegetation patterns are often reported in tropical riparian buffers used for reducing runoff impacts (Luke *et al*., 2018; Wilts *et al*., 2023). In Lake Tondano, the existing vegetation composition already provides basic riparian cover, but continued tourism development and shoreline modification (Warouw *et al*., 2022) may further alter species composition. Therefore, management efforts should consider maintaining both herbaceous and woody species to avoid excessive simplification of riparian vegetation structure, based on the structural information presented in Table 1 rather than on untested functional assumptions.

Quantitative Vegetation Structure

Quantitative analysis revealed considerable variation in species importance within the riparian community (Table 2). The highest relative abundance (Kr) was observed in *Cyperus papyrus* (10.84%), followed closely by *Urochloa mutica* (10.50%). The highest relative frequency (Fr) was also recorded in Poaceae members, particularly *U.*

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mutica (8.49%), indicating that this species was widely distributed across sampling plots rather than being concentrated in only a few locations. These patterns suggest that grasses and sedges form the main horizontal structure of the riparian zone around Lake Tondano, as also reported in other tropical riparian and wetland environments with fluctuating hydrological conditions (Aziz *et al*., 2020; Kadir & Bahagia, 2019).

The Importance Value Index (IVI) ranged from 8.14% (*Diplazium esculentum*) to 90.83% (*Ficus septica*) (Table 2). The very high IVI of *F. septica* was mainly caused by its high relative dominance (Dr = 75.28%), reflecting large stem size and canopy coverage rather than high individual numbers. This indicates that a few large woody individuals can strongly influence structural characteristics of the riparian zone. *Metroxylon sagu* (IVI = 29.65%) and *Cyperus papyrus* (IVI = 21.81%) also showed relatively high IVI values, suggesting that they contribute notably to overall community structure. The presence of *M. sagu* is ecologically relevant, as sago palm is known to be associated with wet and swampy environments and contributes to soil stability through its root system, although this study did not directly measure its functional effects (Ehara *et al*., 2018).

The Shannon–Wiener diversity index (H′ =2.65) indicates moderate to high species diversity (Table 2). According to Magurran (2021), such values generally reflect relatively balanced species distribution, where no single species completely excludes others, even though some species may be structurally dominant. In the context of Lake Tondano, this diversity level suggests that the riparian vegetation still maintains a mix of grasses, herbs, ferns, and woody species. However, this index alone cannot determine ecosystem stability or function, and it should be interpreted only as a description of species distribution based on abundance data.

When compared with other Indonesian riparian and riverside ecosystems, the dominance of a few structurally important species together with moderate diversity is a common pattern. For example, studies in riverbank vegetation in Sulawesi and Java have shown that *Ficus* species often have high dominance values because of their large size, even when their individual numbers are limited (Siappa *et al*., 2016; Zaharah *et al*., 2016). This suggests that the pattern observed in Lake Tondano is not unusual but fits within broader tropical riparian vegetation characteristics. Nevertheless, differences in land use, disturbance intensity, and hydrological regime can strongly influence these structural patterns.

The quantitative structure presented in Table 2 indicates that the riparian community is shaped by both numerically abundant herbaceous species and structurally dominant woody species. Grasses and sedges determine much of the ground and mid-layer cover, while a small number of large trees strongly influence vertical structure. These results describe how species are distributed and how important they are within the community, but they do not directly measure ecological functions such as erosion control or nutrient retention. Therefore, interpretations about function should be made cautiously and based mainly on structural indicators and supporting literature, rather than being treated as direct evidence of ecosystem performance.

Ecological Function Evaluation

Ecological functional assessment showed that species with higher IVI values were more strongly associated with estimated nutrient retention and sediment stabilization (Table 3). *Cyperus papyrus* and *Phragmites australis* were associated with relatively high estimated nutrient removal (45-60% for nitrogen and phosphorus), mainly through dense root mats that slow water flow and trap fine particles. *Ficus septica* and *Metroxylon sagu*, which have deeper and more developed root systems, were associated with higher estimated erosion reduction (30-50%) by improving substrate cohesion and reducing surface runoff. These values are not direct measurements from this study but are derived from structural indicators combined with reference values from previous tropical riparian studies, as summarized in Table 3.

These patterns are in line with studies showing that tropical riparian vegetation can reduce nutrient and sediment transport through mechanisms such as root uptake, canopy interception, and litter accumulation (Mayer *et al*., 2007; Mello *et al*., 2017). In this study, the community level averages for nitrogen and phosphorus reduction were estimated at 38-52%, while erosion reduction ranged from 29-41%

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(Table 3). These estimates suggest that the current riparian vegetation around Lake Tondano has the potential to function as a natural buffer, although the actual effectiveness in the field may vary depending on rainfall intensity, land use, and maintenance of vegetation cover.

The interpretation of these functional roles should be made cautiously. The estimates presented in Table 3 are based on vegetation structure (such as IVI and growth form) and comparison with published studies, rather than on direct measurements of nutrient concentration or sediment flux. Therefore, the results describe potential or likely functions rather than proven performance at specific sites. Similar approaches have been used in restoration and assessment studies where structural vegetation data are linked to expected ecological functions (Marconato *et al*., 2015; Luke *et al*., 2018).

Human activities around Lake Tondano, including agriculture, settlement, and tourism, continue to influence water quality and shoreline condition (Hendratta *et al*., 2024b; Warouw *et al*., 2022). Increased nutrient input and sediment load from these activities may exceed the buffering capacity of existing riparian vegetation, especially where vegetation cover is fragmented or replaced by built structures. Changes in land cover in the Tondano watershed between 2002 and 2015 also indicate increasing pressure on natural vegetation, which may reduce long-term riparian function if not managed carefully (Rotinsulu *et al*., 2018).

Based on the structural and functional indicators in this study, species with high IVI such as *Ficus septica*, *Cyperus papyrus*, and *Metroxylon sagu* appear to be important components of the riparian system. However, their role in filtration and erosion control is inferred from structure and literature rather than directly tested. Conservation and restoration programs should therefore prioritize maintaining vegetation cover and species diversity, while also supporting future studies that directly measure nutrient and sediment dynamics to validate these functional assumptions.

These results also relate to broader management goals. Riparian restoration is often linked to improving water quality and protecting terrestrial aquatic transition zones, which are relevant to SDG 6 (Clean Water and Sanitation) and SDG 15 (Life on Land). In the case of Lake Tondano, strengthening buffer zones, replanting native species, and reducing excessive agricultural chemical use may support riparian function, but the effectiveness of these actions should be monitored carefully and evaluated with field-based measurements rather than assumed solely from vegetation structure.

RESEARCH LIMITATIONS

This study has several limitations that should be acknowledged. First, the ecological functions attributed to riparian vegetation including pollutant filtration and sediment stabilization are based on estimated values derived from published tropical riparian studies and structural vegetation indicators (IVI, growth form), rather than on direct field measurements of nutrient concentrations, sediment flux, or erosion rates at the study sites. Consequently, the quantitative estimates presented in Table 3 represent potential functional capacity and should not be interpreted as measured performance data for Lake Tondano specifically. Second, the absence of paired water quality measurements upstream and downstream of the riparian zones limits the ability to directly attribute changes in water or sediment quality to the recorded vegetation. Third, species identification in the field relied primarily on morphological characteristics and regional flora references; molecular verification was not performed, which may introduce minor taxonomic uncertainty for morphologically similar species. Future research should incorporate direct hydrological and biogeochemical measurements to validate the functional roles inferred in this study.

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Table 2. Analysis of Riparian Vegetation Structure Lake Tondano

No	Species	K	Kr (%)	F	Fr (%)	D	Dr (%)	IVI (%)	Pi	Pi*lnPi
1	*Leersia hexandra* Sw	0.098	9.811	0.082	8.210	0.0025	0.248	18.269	0.098	−0.228
2	*Colocasia esculenta*	0.071	7.057	0.070	6.963	0.0028	0.279	14.299	0.071	−0.187
3	*Ipomoea aquatica*	0.057	5.680	0.062	6.247	0.0012	0.121	12.048	0.057	−0.163
4	*Cyperus platystylis*	0.065	6.540	0.067	6.704	0.0042	0.415	13.659	0.065	−0.178
5	*Vigna luteola*	0.050	4.991	0.059	5.856	0.0007	0.071	10.919	0.050	−0.150
6	*Urochloa mutica* (Forssk.) T.Q. Nguyen	0.105	10.499	0.085	8.493	0.0031	0.312	19.305	0.105	−0.240
7	*Dinebra chinensis* (L.).	0.072	7.229	0.070	7.048	0.0014	0.143	14.419	0.072	−0.190
8	*Ischaemum latifolium* ((Spreng.) Kunth	0.078	7.745	0.073	7.295	0.0031	0.307	15.347	0.078	−0.198
9	*Ficus septica*	0.081	8.089	0.075	7.455	0.7528	75.282	90.827	0.081	−0.203
10	*Phragmites australis* (Cav.) Trin. ex Steud.	0.052	5.164	0.060	5.956	0.0082	0.818	11.937	0.052	−0.153
11	*Acrostichum aureum* (L.)	0.045	4.475	0.056	5.545	0.0038	0.381	10.401	0.045	−0.139
12	*Cyperus papyrus*	0.108	10.843	0.086	8.632	0.0234	2.337	21.812	0.108	−0.241
13	*Metroxylon sagu*	0.048	4.819	0.058	5.754	0.1908	19.076	29.649	0.048	−0.146
14	*Ludwigia octovalvis*	0.038	3.787	0.051	5.101	0.0008	0.081	8.968	0.038	−0.124
15	*Diplazium esculentum* (Retz.) Sw.	0.033	3.270	0.047	4.740	0.0013	0.129	8.140	0.033	−0.112
	Total H'					**1.0001**				**2.652**

Table 3. Functional Role of Dominant Riparian Species

Species	IVI (%)	Estimated N/P Removal (%)	Estimated Erosion Reduction (%)	Main Mechanism
Cyperus papyrus	21.812	45-60	25-35	Root uptake, sedimentation
Ficus septica	90.827	30-45	40-55	Deep roots, canopy protection
Metroxylon sagu	29.649	35-50	30-45	Substrate stabilization
Urochloa mutica	19.305	40-55	20-30	Surface filtration
Community Average	-	38-52	29-41	Multi-species integration

Estimates are based on a meta-analysis of tropical riparian studies (Mello et al. (2017) adjusted to local Lake Tondano conditions.

4. CONCLUSION

Riparian vegetation around Lake Tondano shows moderate to high diversity (H′ = 2.65) and retains structural capacity to reduce estimated nutrient loads and erosion. The dominance of disturbance-tolerant species from Poaceae and Cyperaceae, particularly in areas adjacent to agricultural land and settlements, reflects the ongoing influence of anthropogenic activities on riparian vegetation composition. Dominant species such as *C. papyrus* and *F. septica* provide essential ecosystem services that mitigate eutrophication and sedimentation. Conservation and restoration of riparian zones using native

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species are vital for maintaining water quality and supporting Sustainable Development Goals (SDGs) 6 and 15.

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