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Original Research

Nutrient Dynamics and Recovery Potential In The Tukad Badung River, Indonesia

I Made Wahyu Wijaya [1†], I GD Yudha Partama [1], I Ketut Sumantra [2], Kailas Deoram Ahire[3], Fransiskus Vebrian Kenedy[4]

[1] Regional Planning and Rural Area Study Program, Postgraduate Program, Universitas Mahasaraswati Denpasar, Jalan Kamboja No. 11 A, Denpasar, Bali, Indonesia, 80233, Indonesia, E-Mails: wijaya@unmas.ac.id, yudhapartama@unmas.ac.id

[2] Agrotechnology Study Program, Faculty of Agriculture and Business, Universitas Mahasaraswati Denpasar, Jalan Kamboja No. 11 A, Denpasar, Bali, Indonesia, 80233, Indonesia, E-Mails: ketut.sumantra@unmas.ac.id

[3] Department of Environmental Science, K.R.T. Arts, B.H. Commerce, A.M. Science (KTHM) College, Nashik, Maharashtra, India, India

[4] Environmental Engineering Study Program, Faculty of Engineering, Universitas Mahasaraswati Denpasar, Jalan Kamboja No. 11 A, Denpasar, Bali, Indonesia, 80233, Indonesia, E-Mails: febriankenedy@gmail.com

[†] Corresponding author: I Made Wahyu wijaya: wijaya@unmas.ac.id

Abstract: This study explores the spatiotemporal variations in nitrogen and phosphorus pollutants in the Tukad Badung River, an essential water source for Bali's communities, increasingly impacted by agricultural, domestic, and industrial discharges. Bi-daily sampling at six strategically selected sites along the river's 18-kilometer stretch revealed substantial fluctuations in water quality, with downstream sites consistently exhibiting elevated pollutant concentrations. Ammonia concentrations varied from 1.5 to 4.2 mg/L, nitrate levels ranged from 5.0 to 11.6 mg/L, and total phosphorus concentrations spanned 0.5 to 2.5 mg/L, all of which were highest during afternoon sampling, likely due to reduced flow and increased anthropogenic inputs. Total suspended solids (TSS) exhibited temporal and spatial variability, ranging from 80 to 127 mg/L, with the highest concentrations observed at midstream sites, suggesting localized sedimentation from human activities. The nutrient dynamics displayed marked temporal variations, with concentrations rising during afternoon hours, reflecting shifts in human activity and changes in river flow conditions. Furthermore, the study assessed nutrient recovery technologies, such as precipitation and adsorption, which were able to recover up to 80% of extractable nutrients. These findings not only characterize the pollution trends but also highlight the potential of nutrient recovery techniques in reducing dependency on synthetic fertilizers. This research emphasizes the need for integrated watershed management and adaptive recovery strategies to mitigate nutrient pollution and enhance the sustainability of river ecosystems for future generations.

Key Words	Circular economy; Nutrient recovery; Nutrient concentration; River; Water quality
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1. INTRODUCTION

Rivers are vital ecosystems that support numerous communities worldwide, providing essential water resources for domestic, agricultural, and industrial use. However, rapid urbanization and industrialization have significantly impacted the health of river systems, leading to widespread pollution that threatens water quality and ecosystem integrity (Khonok et al., 2022; Wu et al., 2023). Nevertheless, the swift process of urbanisation and industrialization has resulted in concerning levels of pollution in numerous river systems, posing a threat to both the quality of water and the health of ecosystems. In particular, the Tukad Badung River, located in Bali, Indonesia, faces increasing pollution from agricultural runoff, domestic wastewater, and industrial discharges (Wijaya et al., 2023). This has resulted in elevated levels of nitrogen and phosphorus, key contributors to eutrophication and degradation of aquatic habitats (Ciawi et al., 2022).

The Tukad Badung River covers approximately 30 kilometers and has a watershed area of 37.7 square kilometers. It is an important water source for nearby villages (Nyoman Wiarta et al., 2008). Despite its significance, the river is under constant threat from the influx of solid and liquid waste generated by various human activities within its watershed. The increased flow of pollutants, particularly nitrogen and phosphorus compounds, poses a serious threat to the river's ecological balance and the welfare of downstream community (Ciawi et al., 2022). An interdisciplinary research effort is essential to address the complex challenges of river pollution (Rey-Martínez et al., 2024a; Romero et al., 2021). The present study aims to investigate the complex interactions of nitrogen and phosphorus pollution in the Tukad Badung River, with a focus on identifying methods to extract these nutrients from the stream water. This research is driven by a strong commitment to both environmental stewardship and the ideals of the circular economy.

This study is centred around an innovative method for preserving rivers and managing their resources. This project aims to explore the patterns of nitrogen and phosphorus levels in stream water and develop innovative methods for recovering nutrients. Its goal is to establish a connection between environmental conservation and the sustainable use of resources. Recent studies on nutrient recovery from polluted waters have highlighted innovative approaches to managing nutrient-rich wastewater, with potential for restoring water quality and reducing the environmental impact of nutrient discharges (Betti & Nurhayati, 2022; Katkaew & Chamchoi, 2024; Y. Li et al., 2024). Methods such as nutrient precipitation, adsorption, and biological treatments have been shown to recover valuable resources, including nitrogen and phosphorus, thus contributing to the circular economy (Antunes et al., 2022; Zarei, 2020). However, while these methods have been explored in various contexts, there remains a significant gap in applying such strategies to river ecosystems, particularly in Southeast Asia, where nutrient management is often insufficient or overlooked (Samuel Olugbenga et al., 2024; Sauvé et al., 2021). Given the current state of rivers globally, which is characterised by an unparalleled degree of pollution, it is crucial to urgently devise efficient and scalable measures to protect these precious ecosystems (Suwarno et al., 2014; Vigiak et al., 2023; Wijaya et al., 2023). This research aims to fill that gap by investigating nutrient dynamics in the Tukad Badung River and exploring recovery techniques in alignment with circular economy principles. By focusing on the potential for sustainable nutrient recovery, this study contributes to a growing body of work on managing river pollution through innovative, resource-efficient approaches. While previous studies have primarily concentrated on wastewater treatment plants few have examined the spatial and temporal variations of nutrients in river systems, especially in regions with limited pollution control infrastructure (Rey-Martínez et al., 2024b). This study thus positions itself at the intersection of river pollution management and sustainable resource recovery, offering novel insights into the application of circular economy principles in river ecosystems. By integrating meticulous data collection, analysis, and experimentation, this research seeks to provide a valuable contribution to the growing field of river conservation and sustainable water management, as well as promote the concepts of the circular economy worldwide (Díaz et al., 2024; Piash et al., 2021).

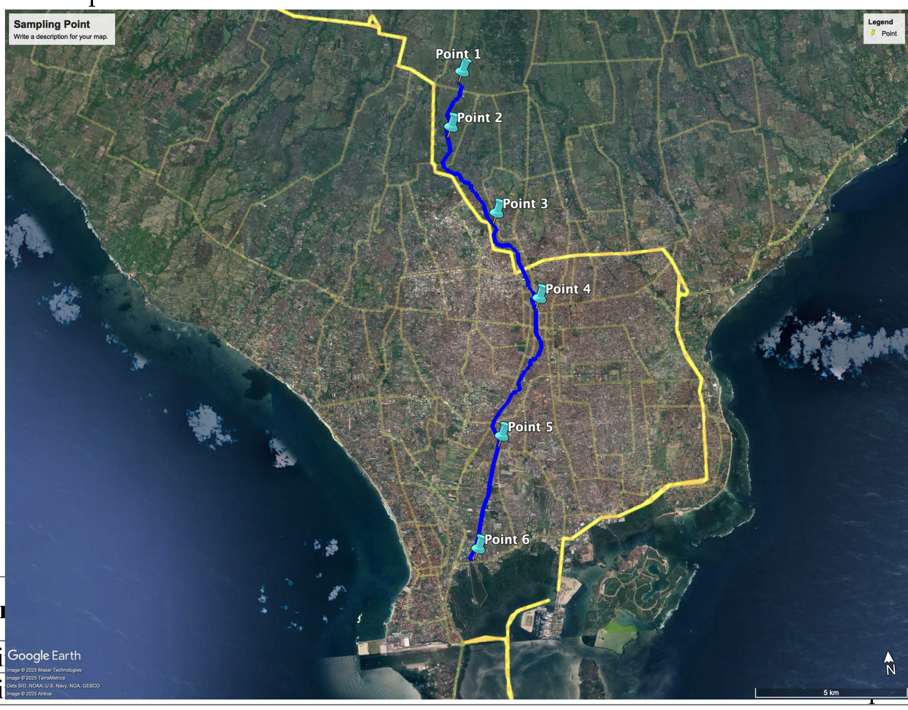
Incorporating circular economy concepts into river management involves not only mitigating pollution but also recovering valuable resources such as nitrogen and phosphorus, which can be transformed into fertilizers or bioenergy substrates (Slootweg, 2020; Zvimba et al., 2021). Such strategies not only reduce dependency on synthetic fertilizers but also enhance resource efficiency and support long-term ecological sustainability. Therefore, this study advocates for integrated watershed management strategies that embrace both pollution control and resource recovery, ensuring the resilience of river ecosystems while contributing to sustainable development goals

2. MATERIALS AND METHODS

The methodology employed in this study involves a systematic approach to data collection, analysis, and experimentation aimed at elucidating nitrogen and phosphorus trends in the Tukad Badung River and exploring methods for nutrient recovery from stream water. The research is structured into distinct phases, each designed to achieve specific objectives in a methodological rigor. Prior to commencing fieldwork and laboratory experiments, meticulous preparations were undertaken to ensure the smooth execution of the research activities. Additionally, a comprehensive inventory of equipment, materials, and personnel was conducted to facilitate efficient data collection and analysis throughout the research period.

2.1 Sampling Points

Sampling points were strategically selected along an 18-kilometer stretch of the Tukad Badung River, divided into upstream, midstream, and downstream zones (**Fig.1**). This zoning approach enables the capture of spatial variations in nutrient concentrations along the river's course. Six sampling points were designated, with two points in each zone, to ensure adequate coverage of the river's spatial dynamics. The selection of sampling points adhered to established guidelines outlined in SNI 03-7016-2004 Procedure for Water Quality Sampling in River Drainage Areas for Monitoring Purposes, ensuring consistency and reliability in data collection. The sampling coordinates are provided in the Table 1.



No	Sampli			ne
1	Poi			eam
2	Poi			eam
3	Point 3	8°37'27.85"S	115°12'7.48"E	Midstream
4	Point 4	8°39'0.50"S	115°12'45.12"E	Midstream

5	Point 5	8°41'21.13"S	115°11'53.05"E	Downstream
6	Point 6	8°43'16.77"S	115°11'18.22"E	Downstream

The selection of these locations aimed to represent the diverse pollution sources within the river's watershed and to reflect variations in water quality as influenced by agricultural runoff, domestic wastewater, and industrial effluents.

- **Upstream locations (Sampling Points 1 and 2)** were chosen to capture the relatively cleaner water entering the river before major pollution sources.
- **Midstream locations (Sampling Points 3 and 4)** represent areas influenced by both upstream contributions and localized pollution from nearby settlements and industries.
- **Downstream locations (Sampling Points 5 and 6)** capture the cumulative effects of pollution, with higher concentrations of nutrients likely due to agricultural runoff, domestic wastewater, and reduced dilution from lower flow conditions.

This design ensures that the sampling points span the river's pollution gradient, enabling a thorough analysis of nutrient dynamics along the river. The rationale for selecting these six points is supported by the literature on river pollution dynamics, which emphasizes the need for a spatially representative sampling strategy to understand variations in nutrient concentrations and their impact on river ecosystems (Betti & Nurhayati, 2022; Ciawi et al., 2022).

2.2 Sampling Collection

Sampling activities were conducted twice daily, at 08:00 AM and at 07.00 PM, to capture diurnal variations in nutrient levels and peak domestic wastewater conditions. The 08:00 AM represents the morning sampling, when domestic and industrial discharges are typically lower, and the water quality is less impacted by human activities. The 07:00 PM was selected for the afternoon sampling to capture peak pollution times, as this period often coincides with higher domestic wastewater inputs and lower river flow due to reduced hydrological activity. Additionally, nutrient concentrations such as ammonia and phosphate tend to be elevated in the afternoon due to the accumulation of pollutants throughout the day and reduced water flow, which limits dilution. This diurnal variation in sampling times is consistent with findings from other studies that demonstrate the significant impact of human activity on water quality, particularly during peak hours when domestic wastewater and industrial effluents contribute to higher nutrient concentrations (Conley et al., 2009; Saily & Setiawan, 2021). These time intervals help provide a comprehensive view of the temporal dynamics of nutrient concentrations within the river. At each sampling point, water samples were collected using standardized techniques outlined in the SNI 6989.57-2009 standard for surface water sampling methods. A total of five litres of water was collected from each sampling point during each sampling event, ensuring an adequate sample size for subsequent laboratory analysis.

2.3 Laboratory Analysis

Upon collection, water samples were transported to the laboratory for a comprehensive analysis. The key water quality parameters include total suspended solids (TSS), ammonia (NH_3^-), nitrite (NO_2^-), nitrate (NO_3^-), total nitrogen (Total N), and total phosphorus (Total P) were analysed by following the standard method (APHA/AWWA/WEF, 2017). Spectrophotometric analyses were conducted using state-of-the-art equipment and methodologies, to ensure accuracy and precision in measuring nutrient concentrations.

2.4 Data Analysis

Data collected from both field sampling and laboratory experiments were subjected to rigorous statistical analysis to identify spatial and temporal trends in nitrogen and phosphorus concentrations along the Tukad Badung River. Additionally, graphical representations such as maps and trend charts were generated to visualize spatial and temporal variations in nutrient concentrations, aiding in the interpretation of research findings. The culmination of data analysis and experimentation enabled the interpretation of findings and the formulation of evidence-based conclusions. The implications of the observed nutrient trends and the efficacy of nutrient recovery strategies were critically evaluated in the context of river conservation and sustainable water management. Insights derived from this study contribute to the body of knowledge surrounding nutrient dynamics in river ecosystems and provide valuable guidance for policymakers, environmental practitioners, and stakeholders involved in water resource management and conservation efforts.

An examination of nitrogen and phosphorus levels at six specific sampling locations along the Tukad Badung River yields useful information about the spatial and temporal changes in nutrient pollution within the river ecosystem. The morning sample session at 08:00 AM and the afternoon sampling session at 07:00 PMexhibited clear patterns in nutrient levels, indicating fluctuations throughout the day and potential sources of pollution within the watershed. The following analysis provides a comprehensive examination of each metric, followed by a discussion of its impact on water quality and aquatic life.

3. RESULT AND DISCUSSION

The nutrient concentrations in the Tukad Badung River are varied across different sampling points, with higher concentrations observed downstream. This spatial variation can be attributed to a combination of natural processes and anthropogenic activities within the watershed. The land use map of Denpasar City, shown in Fig. 2, illustrates the land use surrounding the sampling points. Upstream areas (Sampling Points 1 and 2) generally exhibited lower nutrient concentrations, likely due to limited human activity and agricultural runoff. However, as the river flows downstream, nutrient concentrations increase, particularly at Sampling Points 5 and 6, which are more heavily influenced by urban areas and home industrial effluents. The increased nutrient concentrations in these areas could be linked to runoff from agricultural lands, wastewater discharges from domestic and industrial sources, and reduced dilution capacity in stagnant flow conditions. The land use in the surrounding watershed, including agriculture, urbanization, and industrial zones, significantly contributes to the nutrient dynamics observed in these areas (Ciawi et al., 2022; Raeisi et al., 2022). The overall measured parameter concentration are shown in **Table** .

Nutrient concentrations in the Tukad Badung River demonstrated clear temporal variations, with higher values recorded during afternoon sampling (07:00 pm) compared to morning sampling (08:00 am). This pattern can be explained by several factors. Diurnal biological activity, such as increased microbial decomposition of organic matter, typically leads to elevated nutrient levels in the afternoon. Additionally, the discharge of domestic wastewater tends to be higher during peak hours, contributing to increased nutrient loads in the afternoon. Furthermore, reduced flow rates during the afternoon decrease the river’s ability to dilute pollutants, exacerbating the accumulation of nutrients. These temporal dynamics are influenced by both ecological processes, such as biological activity and sedimentation, as well as socio-economic factors, including human activities that lead to higher discharges of domestic and industrial waste during afternoon hours (Conley et al., 2009; X. Li et al., 2023).

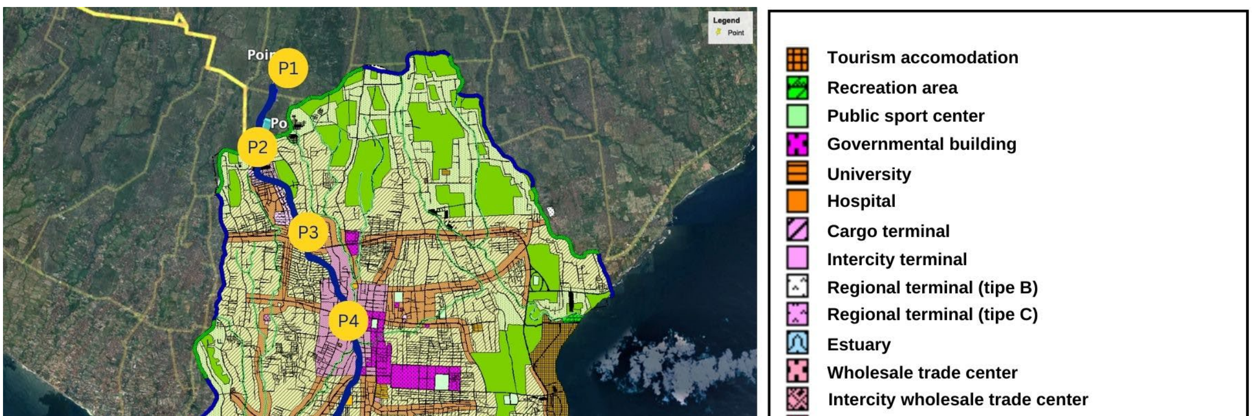


Fig. 2. Land use map of Denpasar City surround the sampling points

Table 2. The concentration of measured parameters (mg/L)

Parameters	Sampling Time	Sampling Points					
		1	2	3	4	5	6
Total Suspended Solid	08.00 AM	12.00	19.00	20.00	18.00	9.00	12.00
	07.00 PM	18.00	20.00	32.00	14.00	17.00	10.00
Ammonia (NH_3 -N)	08.00 AM	0.57	0.00	0.09	0.25	1.54	1.96
	07.00 PM	0.62	0.00	1.27	0.19	2.00	0.68
Nitrit (NO_2 -N)	08.00 AM	0.09	0.00	0.03	0.13	0.10	0.16
	07.00 PM	0.77	0.00	0.70	0.93	0.73	0.91
Nitrat (NO3 -N)	08.00 AM	1.22	1.39	1.23	1.91	1.41	1.19
	07.00 PM	4.58	1.89	9.21	2.90	3.40	3.45
Total Phospat	08.00 AM	0.01	0.07	0.14	0.28	0.65	0.49
	07.00 PM	0.14	0.00	0.48	0.31	0.70	0.52
Total Nitrogen	08.00 AM	1.89	1.39	1.36	2.29	3.06	3.31
	07.00 PM	5.97	1.89	11.17	4.02	6.14	5.03

3.1 Total Suspended Solids (TSS)

The Total Suspended Solids (TSS) values exhibited substantial variability across different sampling stations and time points, reflecting both spatial and temporal fluctuations in sediment loads and water quality dynamics. Spatially, TSS concentrations (as shown in Fig. 3) demonstrated notable differences between sampling locations. Sample Points 3 and 4, situated in the central section of the stream, consistently recorded higher TSS levels than the upstream (Sample Points 1 and 2) and downstream (Sample Points 5 and 6) sites. This spatial distribution suggests that sedimentation and erosion in the middle reaches of the river are concentrated in particular zones, likely influenced by anthropogenic activities such as agriculture, construction, and urbanization (Baiyin et al., 2024; Silva-Gálvez et al., 2024; Yuan et al., 2023). The TSS levels exhibited temporal variation between morning and afternoon sampling sessions. Generally, TSS concentrations tended to increase during the afternoon sessions. This pattern may be attributed to sediment resuspension and heightened water flow from adjacent land areas, which likely occurred during daylight hours. (Noor et al., 2023; South & Nazir, 2016; Z. Wang & Liu, 2023). The fact that sediment transport processes within the river ecosystem vary during the day emphasises the dynamic nature of these processes. It also emphasises the need to consider changes over time when assessing water quality.

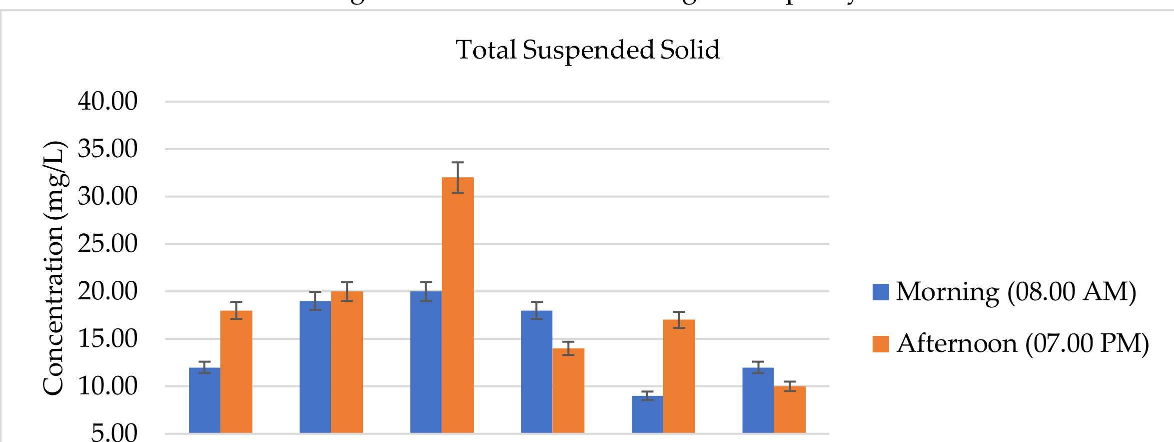


Fig. 3. Total suspended solid (TSS) concentration trend

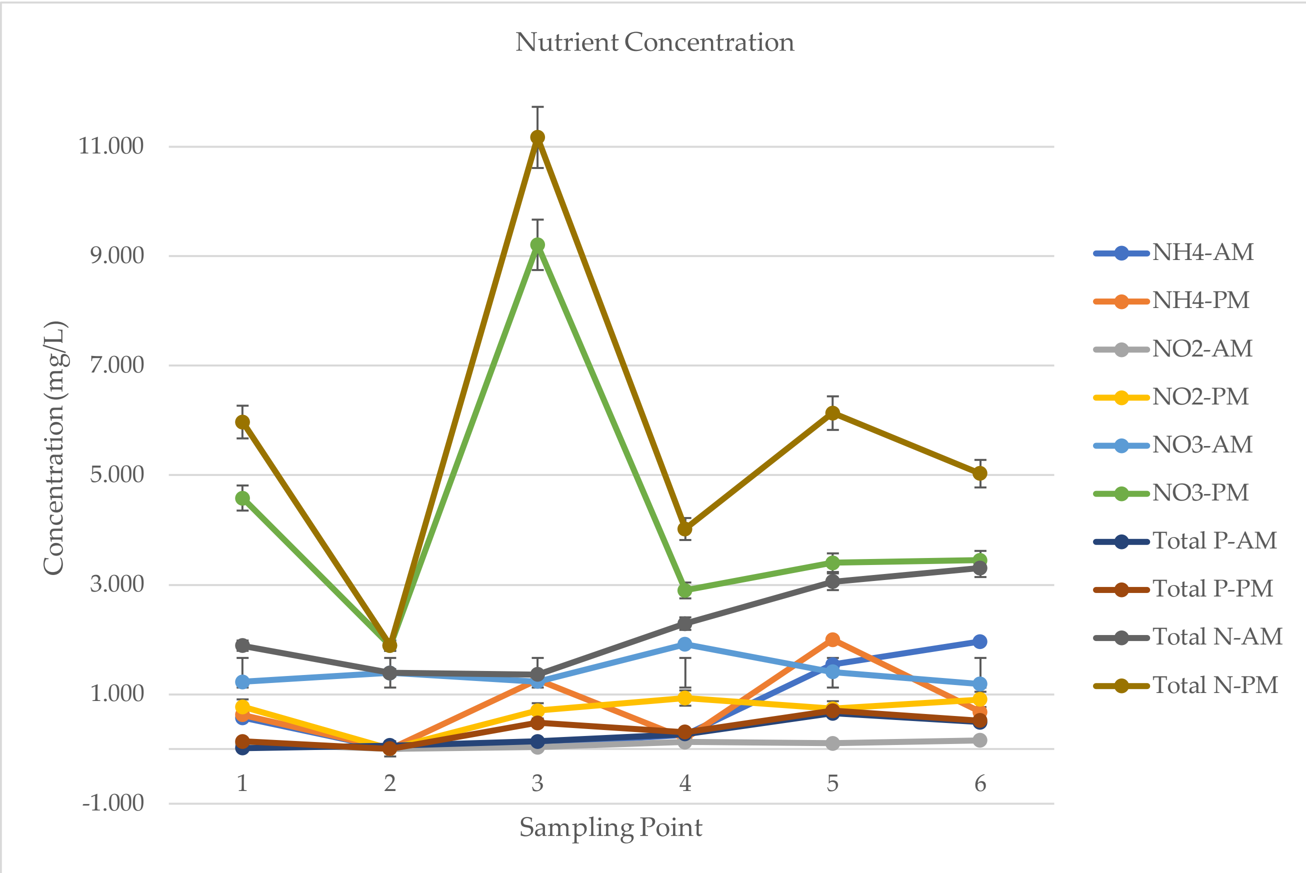
Elevated TSS (total suspended solids) concentrations can have substantial consequences for the hydrodynamics of water streams and the biodiversity of aquatic ecosystems. Excessive sedimentation can hinder water clarity, leading to a decrease in the amount of light that can penetrate the water and lowering the ability of aquatic plants to carry out photosynthesis (Khonok et al., 2022; Soedjono et al., 2018; Suantara et al., 2020). Consequently, this can disturb the habitats at the bottom of the river and modify the natural equilibrium of the river ecosystem. In addition, water containing silt can suffocate aquatic environments, such as gravel beds and riffles, which are vital for fish reproduction and the habitat of macroinvertebrates. In addition, high levels of total suspended solids (TSS) can lead to greater turbidity, which decreases visibility for aquatic creatures and hinders predator-prey interactions (García-Avila et al., 2023; Rowland et al., 2021; Ural-Janssen et al., 2024). Suspended silt particles can obstruct the respiratory organs of fish, disrupt the feeding process of filter-feeding animals, and inhibit the growth of fish embryos and larvae. As a result, elevated levels of total suspended solids (TSS) can have a negative impact on the diversity of aquatic life, causing a decrease in populations and degradation of the environment over a period (Dory et al., 2024; Qiu et al., 2024; Sumantra et al., 2023).

Multiple reasons can lead to elevated levels of Total Suspended Solids (TSS) in river water, such as soil erosion originating from agricultural fields, construction sites, and deforested areas (Wiegers & Larsen, 2024; Zarei, 2020). Urban runoff, which includes particles from roads, rooftops, and paved surfaces, can increase the concentration of total suspended solids (TSS) in river systems. In addition, natural phenomena such as bank erosion, streambed scouring, and the suspension of sediment during periods of high flow can increase the amount of silt in rivers (Darji et al., 2022; Nugraha et al., 2020). Human activities, such as clearing land, mining, and inappropriate waste disposal, can worsen sedimentation problems by increasing the pace at which soil erodes and silt is carried into bodies of water. Insufficient soil conservation methods, such as inappropriate land management and deforestation, can exacerbate sedimentation issues, resulting in diminished water quality and the loss of habitats in river ecosystems (Kaown et al., 2023).

The examination of TSS concentrations in the Tukad Badung River emphasises the fluctuation in sediment loads across space and time and the possible consequences of elevated TSS levels on the quality of water and aquatic organisms. To tackle sedimentation problems, it is necessary to implement holistic approaches to managing watersheds. These approaches should incorporate steps to conserve soil, plan land use effectively, and implement erosion control procedures (Darji et al., 2022). By doing so, we may reduce the amount of sediment that is transported to water bodies and protect river ecosystems for future generations.

3.2 Nutrient Concentration

The analysis of nutrient dynamics in the Tukad Badung River highlights distinct temporal and spatial variations in ammonia, nitrate, and phosphorus concentrations. These parameters exhibited similar trends across sampling points, with higher concentrations found downstream and during afternoon sampling sessions. The increases in these nutrient concentrations are likely driven by anthropogenic influences, such as urban wastewater discharges and agricultural runoff. Notably, total phosphorus and ammonia concentrations were highest at downstream sites, reflecting the cumulative effects of human activities, while nitrate concentrations showed a more consistent increase from upstream to downstream. These trends suggest that nitrogen and phosphorus are primarily introduced into the river through domestic and industrial waste, as well as agricultural activities that contribute to nutrient loading. According to the **Table 2**, the trends comparison between each nutrient concentration is provided in the **Fig 4.**



indicates that there are specific sources of pollution, such as industrial waste or urban runoff, that are causing higher levels of ammonia in the lower parts of the river (**Fig 2**). Temporarily, ammonia concentration varied between the morning and afternoon sampling. Typically, the levels of ammonia were greater during the afternoon sampling sessions at all sample locations. The diurnal pattern seen can be explained by the increased biological activity and decomposition of organic matter during daylight hours, resulting in an enhanced ammonia production and its release into the water column (Conley et al., 2009; Ezzati et al., 2023). In addition, lower water flow rates and sluggish circumstances in the afternoon might lead to an increase in ammonia levels and a decrease in the ability to dilute it.

Elevated concentrations of ammonia can adversely affect water quality and the species residing in aquatic ecosystems. Elevated levels of ammonia are highly detrimental to aquatic creatures, particularly fish and invertebrates (Bartelme et al., 2017; Kim et al., 2010; Pejman Sereshkeh et al., 2024). It impairs respiratory function, damages the gills, inhibits growth, and increases the organism's vulnerability to diseases. Furthermore, elevated ammonia concentrations can disrupt the normal functioning of physiological systems in aquatic organisms, including osmoregulation and metabolic activities. (Chen et al., 2024; Gu et al., 2024). These changes may result in decreased survival rates and impaired reproductive success. Increased ammonia concentrations alter the chemical composition of water, influencing pH levels and changing nutrient cycling in aquatic ecosystems. Ammonia poisoning can indirectly impact other aquatic organisms by disrupting food webs and community dynamics. (Astals et al., 2018; Ha et al., 2023; Muscarella et al., 2021). Consequently, increased levels of ammonia can have substantial negative impacts on the diversity of aquatic life and ecosystems helath, especially in vulnerable regions like spawning grounds and nursery areas.

Numerous factors contribute to increased ammonia levels in river water. Industrial discharges, sewage effluents, and agricultural runoff exemplify point sources of pollution that contribute elevated concentrations of ammonia to aquatic systems. (Trap et al., 2024; Vystavna et al., 2023). Ammonia pollution problems can be exacerbated by ineffective wastewater treatment methods and incorrect organic waste disposal, leading to localized contamination hotspots. Furthermore, natural processes including the decomposition of organic matter and nutrient cycling in aquatic environments might facilitate ammonia generation. (Patterson, 2003; Serra et al., 2023; Yates et al., 2022). An excess of organic materials, such rotting vegetation or animal waste, can stimulate microbial proliferation and ammonification, resulting in increased ammonia emission into the water. Moreover, the existence of stagnant water, diminished water movement, and inadequate dissolved oxygen levels can exacerbate ammonia accumulation and impede the natural processes that alleviate pollution, so intensifying the problem. (Ural-Janssen et al., 2024). To tackle this dilemma, it is essential to deploy comprehensive solutions that target both direct and diffuse sources of contamination. This encompasses enhancing wastewater treatment techniques and advocating for sustainable land use practices to diminish fertilizer inputs and save river habitats for future generations.

The study reveals distinct geographical and temporal patterns in nitrite and nitrate levels, indicating particular localized influences and daily fluctuations in nutrient loads.. Geographically, the levels of nitrite and nitrate showed significant differences among the locations where samples were taken (**Fig 4)** Elevated concentrations of nitrite and nitrate were regularly detected at the sampling points downstream (Sample Points 5 and 6) in comparison to the upstream (Sample Points 1 and 2) and midstream (Sample Points 3 and 4) regions. Specific pollution sources, such as agricultural runoff or industrial discharges, have an impact on the lower parts of the river.

The concentrations of nitrite and nitrate fluctuated during the morning and afternoon sample sessions. The concentrations of nitrite and nitrate were generally higher during the afternoon sampling sessions at all sampling points. Human activities, including agriculture and urban runoff, contribute supplementary nutrients to the river during daylight, elucidating the observed diurnal variation in nutrient levels. This leads to a heightened concentration of nutrients in the water column. Moreover, reduced water flow rates and sluggish conditions in the afternoon may result in nutrient accumulation and diminished dilution capacity (Busico et al., 2024; Flynn et al., 2023).

High levels of nitrite and nitrate in water can have serious consequences for water quality and the organisms that live in it. Nitrite and nitrate are essential nutrients for plant development (Begam et al., 2024; Sorokin et al., 2012). However, when present in excessive amounts, they can lead to eutrophication, algal blooms, and oxygen depletion in aquatic habitats. Excessive nitrogen inputs can trigger algae growth, resulting in the production of thick mats of algae and the eventual depletion of oxygen due to microbial decomposition (van Wijk et al., 2024; Yu et al., 2014). Elevated levels of nitrites can also have a detrimental effect on aquatic organism, including fish and invertebrates, by interfering with their respiratory processes and causing methemoglobinemia, a condition that reduce their blood’s ability to carry oxygen (Carneiro Marques et al., 2023; Ma et al., 2016; Silvestrini et al., 2024). Nitrate, on the other hand indirectly affect aquatic ecosystems by stimulating algal proliferation and altering water chemistry, which can result in shifts in pH levels and nutrient cycle mechanisms. Moreover, increased concentrations of nitrates might pose hazards to human well-being by polluting supplies of potable water, especially in regions that depend on underground water reserves. Several factors contribute to elevated levels of nitrite and nitrate in river water. Agricultural practices, including fertilizer application and livestock husbandry, elevate nitrogen compound concentrations in aquatic bodies via surface runoff and leaching mechanisms. (Arcas-Pilz et al., 2023). Furthermore, the process of urbanisation and industrialization can lead to the contamination of nitrite and nitrate due to the release of nitrogen-rich pollutants in sewage effluents, industrial discharges, and stormwater runoff.

The total nitrogen concentrations in the Tukad Badung River exhibited clear spatial and temporal variations. During the morning sampling at 08:00 AM, total nitrogen concentrations ranged from 1.36 mg/L at Point 3 to 3.31 mg/L at Point 6, with the highest levels observed downstream. The concentrations were relatively lower upstream, particularly at Points 1 (1.89 mg/L) and 2 (1.39 mg/L), indicating that anthropogenic influences such as agricultural runoff and wastewater discharge likely contribute to higher nitrogen levels as the river progresses downstream. In contrast, the afternoon sampling at 07:00 PM showed a noticeable increase in nitrogen concentrations across all points, with values ranging from 1.89 mg/L at Point 2 to 11.17 mg/L at Point 3. The highest recorded concentration of total nitrogen (11.17 mg/L) was observed at Point 3, indicating a significant accumulation of nitrogen in the midstream area, potentially due to increased human activities such as wastewater discharge and biological decomposition during the afternoon. The nitrogen concentrations at Points 5 and 6 (6.14 mg/L and 5.03 mg/L, respectively) remained elevated, although slightly lower than at Point 3.

These temporal variations suggest that total nitrogen concentrations are influenced by both natural processes, such as biological cycling, and socio-economic factors, including peak human activity in the afternoon, leading to higher nutrient discharges. The increase in nitrogen concentrations during the afternoon can likely be attributed to both reduced water flow during off-peak hours, which limits dilution, and increased domestic wastewater contributions, which typically peak in the afternoon. Atmospheric deposition and biological nitrogen fixing are natural processes that can also add nitrite and nitrate to aquatic habitats. Nevertheless, human activities have greatly increased nitrogen pollution problems, resulting in extensive deterioration of water quality and disturbances to ecosystems (Panjwani et al., 2021; Stein & Klotz, 2016; Zhou et al., 2024). The amalgamation of inadequate nutrient management practices, substandard waste disposal, and deficient wastewater treatment infrastructure exacerbates the issue of nitrite and nitrate contamination. This poses considerable issues for river conservation and water resource management. The analysis of nitrite and nitrate concentrations in the Tukad Badung River underscores the complex dynamics of nitrogen pollution and its impact on water quality and the associated ecosystems. A well-coordinated strategy is required to tackle food sources from both point and non-point origins (Lavallais & Dunn, 2023). This can be achieved by implementing effective nutrient management practices and promoting sustainable land use practices. It can protect river ecosystems and ensure the availability of clean and healthy water resources for current and future generations.

The research uncovers noticeable regional and temporal patterns in the levels of total phosphorus, which indicate the presence of localised impacts and daily variations in nutrient loads. Downstream sampling stations (Sample Stations 5 and 6) consistently exhibited higher total phosphorus levels compared to upstream (Sample Points 1 and 2) and midstream (Sample Points 3 and 4) locations. The overall phosphorus levels fluctuated between the morning and afternoon sampling periods. Total phosphorus concentrations were generally higher during afternoon sampling sessions at all sampling stations. Human activities, including agriculture and urban runoff, contribute supplementary nutrients to the river during daylight, elucidating the observed diurnal variation in nutrient levels. This results in an increased concentration of nutrients in the water column (Ezzati et al., 2023; Lu et al., 2024; Xu et al., 2018). In addition, reduced water flow rates and sluggish circumstances in the afternoon can lead to the accumulation of nutrients and a decrease in the ability to dilute them.

High levels of total phosphorus can have a significant impact on the water quality and the organisms that live in it (Conley et al., 2009; Smith & Myers, 2024). Excessive amounts of total phosphorus, an essential nutrient for the growth of algae, can cause eutrophication, algal blooms, and oxygen depletion in aquatic habitats. Elevated phosphorus concentrations can trigger the rapid growth of algae, leading to the development of thick mats of algae that block sunlight from reaching native plants and reduce biodiversity (Correll, 1998; Suryawan et al., 2024; Zhang et al., 2023). Furthermore, the proliferation of algal blooms can result in a reduction in oxygen levels due to the breakdown of organic matter by microorganisms. This can create hypoxic conditions that are detrimental to aquatic animals (Hu et al., 2023).

In addition, elevated quantities of total phosphorus can disrupt the chemical composition of water, causing fluctuations in pH levels and discrupting nutrient cycle systems. Water acidification can have detrimental effects on aquatic creatures, compromising their metabolic functions and reproductive success (Liu et al., 2024; Rey-Martínez et al., 2024b). Phosphorus pollution also pose indirect effect on human health by contaminating drinking water sources, especially in regions that depend on surface water for their supply of safe drinking water (Panasiuk, 2012; Proskynitopoulou et al., 2024; Silva et al., 2023). Agricultural practices, including the application of fertilizers and the rearing of livestock, can lead to increased phosphorus levels in water bodies through surface runoff and leaching (Koulouri et al., 2024; Zhu et al., 2023). Urbanisation and industrialization further lead to the contamination of phosphorus through the release of phosphorus-rich pollutants in sewage effluents, industrial discharges, and stormwater runoff.

Natural processes, such the weathering of phosphorus-rich rocks and the resuspension of silt, can affect phosphorus inputs in aquatic environments. Nonetheless, human activities have markedly exacerbated phosphorus pollution, leading to substantial degradation of water quality and disruption of ecosystems. Inefficient nutrient management, improper waste disposal, and insufficient wastewater treatment facilities worsen phosphorus contamination issues. (Galeano et al., 2023; Galligan & McClanahan, 2024; Ruijter et al., 2016). These factors provide considerable challenges for river conservation and water resource management. The examination of overall phosphorus levels in the Tukad Badung River highlights the intricate nature of nutrient contamination patterns and their effects on the water quality and aquatic ecosystems. It is necessary to implement comprehensive management strategies that address both specific and diffuse sources of contamination. This includes improving nutrient management and promoting sustainable land use practices to protect river ecosystems and ensure the availability of clean and healthy water resources for current and future generations.

3.3 Potential of Nutrient Recovery from Streamwater

The possibility of nutrient recovery from the Tukad Badung River is intricately linked to the tenets of the circular economy. By extracting nutrients like nitrogen and phosphorus from contaminated water, these essential resources can be reused for agricultural applications, thereby diminishing the need on synthetic fertilizers. Nutrient recovery techniques, such as precipitation and adsorption, have demonstrated efficacy in extracting these nutrients from water, with recovered phosphorus and nitrogen being utilized as fertilizers for agriculture or substrates for bioenergy generation.. Studies have demonstrated that such nutrient recovery can result in up to 80% of extractable nutrients being recovered from wastewater (Hofmann et al., 2024a). Implementing these technologies in the Tukad Badung River could significantly reduce dependence on chemical fertilizers, lower environmental impacts, and contribute to a more sustainable and resource-efficient agricultural system. Quantitative forecasts indicate that recovering and repurposing a portion of the nutrients from the river might substantially diminish nutrient loads in agricultural runoff, thus enhancing water quality and mitigating downstream eutrophication.

This study provides valuable insights to support the initiative of nutrient recovery from stream water as part of a circular economy model for wastewater treatment. By analysing the spatial and temporal variations of nutrient pollutants along the Tukad Badung River, the study identifies opportunities for the sustainable management and utilisation of these nutrients to minimise environmental impact and enhance resource efficiency. The findings highlight the significant concentrations of nutrients in the river, including nitrogen and phosphorus. These nutrients, if properly recovered, can serve as valuable resources for various applications, such as agricultural fertilisers, bioenergy production, and aquaculture feed (Hofmann et al., 2024a; Winkler & Straka, 2019; Xiao et al., 2016). By implementing technologies for nutrient recovery, such as nutrient adsorption, precipitation, and biological processes, wastewater treatment facilities can extract these nutrients from stream water and convert them into valuable products, thereby closing the nutrient loop and reducing dependency on synthetic fertilizers and other external inputs (Lin et al., 2016; Marcińczyk et al., 2022; Rey-Martínez et al., 2024b; Sari et al., 2023; Xiao et al., 2016). The alternative of the nutrient recovery techologies have been summarized in the **Table 3**.

Table 3. Summaries of the nutrient recovery technology

Technology	Description	Case Studies	Recovery Efficiency
Nutrient Precipitation	Chemical processes that form insoluble compounds from dissolved nutrients (e.g., struvite precipitation for phosphorus recovery).	Germany: Struvite precipitation in wastewater treatment plants (WWTPs) has been widely adopted for phosphorus recovery.	Up to 90% phosphorus recovery (Hofmann et al., 2024b)
Adsorption	Use of adsorbents (e.g., biochar, activated carbon) to remove nutrients from water.	India: Application of biochar in decentralized treatment systems in rural areas to remove nitrogen from wastewater.	Up to 80% nitrogen recovery (Xiao et al., 2016)
Membrane Filtration	Use of membranes to selectively filter out nutrients from water.	**USA**: Membrane bioreactors (MBRs) used in wastewater treatment plants for nitrogen and phosphorus removal.	70-85% nitrogen and phosphorus recovery (G. Wang et al., 2016)
Biological Processes	Microbial processes such as nitrification-denitrification and algae-based systems.	**China**: Algae-based systems for nutrient recovery in urban wastewater treatment.	50-80% nutrient recovery (Rey-Martínez et al., 2024b)
Electrochemical Methods	Electrochemical processes for nutrient extraction and recovery.	**Sweden**: Electrochemical cells for nitrogen removal from wastewater and agricultural runoff.	60-70% nitrogen recovery (Galeano et al., 2023)
Constructed Wetlands	Engineered wetland systems designed to naturally treat wastewater by supporting nutrient uptake via vegetation.	**Brazil**: Constructed wetlands in rural areas for removing nitrogen and phosphorus from agricultural runoff and domestic wastewater.	50-80% nutrient removal (Darji et al., 2022)
Anammox (Anaerobic Ammonium Oxidation)	Biological process using bacteria to convert ammonia directly into nitrogen gas, bypassing traditional nitrification.	**Netherlands**: Anammox process for nitrogen removal in full-scale wastewater treatment plants.	90-95% nitrogen recovery (Kim et al., 2010)
Phytoremediation	Use of plants to absorb or remove nutrients, particularly nitrogen and phosphorus, from water.	**USA**: Wetland plants used in the Everglades to reduce nutrient loading from agricultural runoff.	50-70% nutrient removal (García-Avila et al., 2023)

The research delineates the spatial distribution of nutrient hotspots throughout the river, highlighting prospective sites for nutrient recovery facilities. By strategically positioning nutrient recovery facilities in proximity to regions with elevated nutrient concentrations, such as urban centers or industrial districts, wastewater treatment operators can enhance resource recovery and reduce transportation expenses related to nutrient extraction and delivery (Soedjono et al., 2017; Sumantra et al., 2022; Wijaya et al., 2017). Furthermore, the temporal variations in nutrient concentrations revealed by the study underscore the dynamic nature of nutrient pollution in river ecosystems. Establishing real-time monitoring systems and adaptive management strategies allows wastewater treatment plants to modify nutrient recovery procedures according to variations in nutrient loads. This method optimizes resource recovery efficiency and reduces environmental effect. This study offers critical data and insights to guide the planning and execution of nutrient recovery activities within a circular economy framework for wastewater treatment. (Antunes et al., 2022; Sauvé et al., 2021; Slootweg, 2020; Zvimba et al., 2021). These projects extract essential nutrients from stream water and transform them into reusable goods like fertilizers or biofuels, so promoting resource conservation, environmental protection, and sustainable development in the Tukad Badung River basin and beyond.

4. CONCLUSION

This study highlights nutrient pollution in the Tukad Badung River, driven by agricultural runoff, domestic wastewater, and industrial discharges. Nutrient recovery technologies, such as precipitation, adsorption, and biological processes, offer promising solutions to reduce nutrient levels, minimize dependence on synthetic fertilizers, and enhance water quality. To improve watershed management, it is essential to integrate these recovery technologies into local infrastructure. Policymakers should focus on decentralized wastewater treatment systems and promote sustainable agricultural practices to reduce nutrient runoff. Strengthening regulatory frameworks for wastewater treatment will further support these efforts. However, challenges remain, including the scalability of recovery methods and the need for cost-benefit analysis to assess their feasibility for large-scale implementation. Future research should address these issues to ensure the practical application of nutrient recovery technologies. In conclusion, this study contributes to sustainable river management by demonstrating the potential of nutrient recovery to address nutrient pollution. The findings offer valuable insights for

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