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Biodegradability index (BDI) as an indicator for effluents quality measurement: A case study based on different industry sectors in Matara District, Sri Lanka

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ABSTRACT

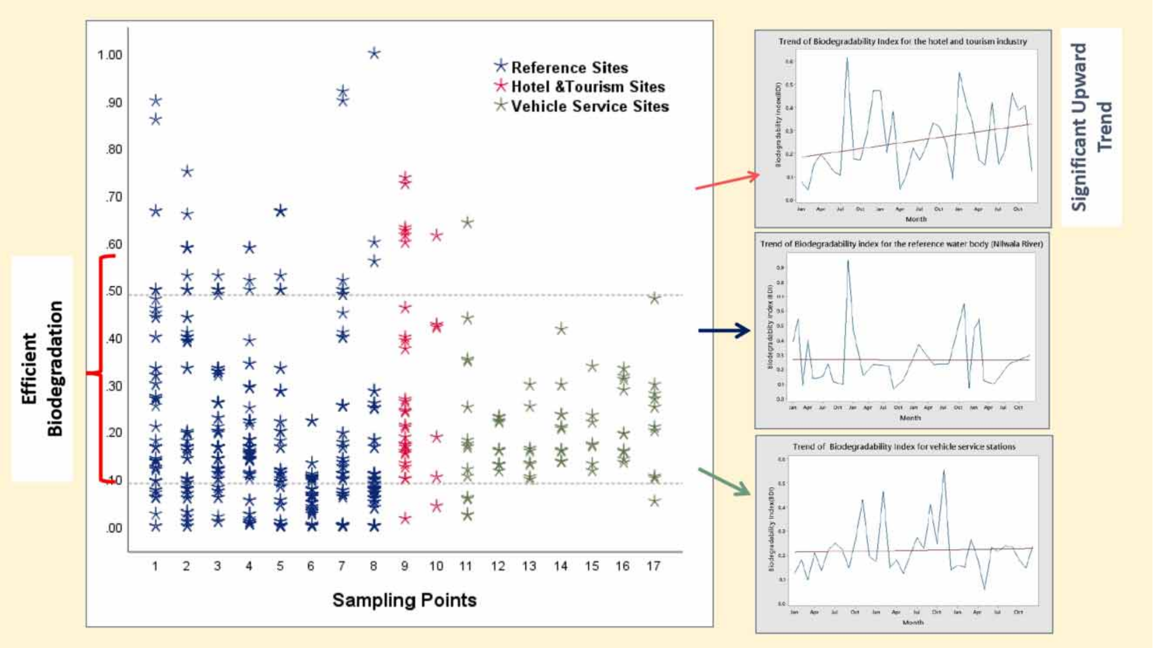
This study addresses the crucial need for appropriate indicators to characterize aquatic pollution, given the challenges posed by unrestricted effluent discharge globally. Focusing on wastewater from hotel and tourism industries and vehicle service stations in Matara District, Sri Lanka, we explored the relationship between biological oxygen demand (BOD) and chemical oxygen demand (COD) through the biodegradability index (BDI). Monthly water samples were collected from January 2019 to December 2022, analyzed using standard methods, and statistically evaluated. Results revealed a significant spatial variation in BDI among industry sites, with a modest temporal change. The BOD:COD ratio exhibited a slight increasing trend over time, suggesting factors beyond temporal influence. BDI correlated significantly with temperature, alkalinity, and total suspended solids (TSS), emphasizing its potential as an indicator. The study underscores the importance of complementing the BOD:COD ratio with other indicators for a comprehensive assessment of industrial effluent quality. This research contributes valuable insights into understanding wastewater characteristics, facilitating informed pollution reduction and control strategies in aquatic systems.

Key words: biodegradability index (BDI), BOD:COD ratio, industrial effluent quality, unregulated effluent discharge, wastewater treatment

HIGHLIGHTS

- Evaluated the biodegradability index (BDI) of two main effluent discharging industries to detect biodegradability changes with the time.
- The trend analysis shows a significant upward trend in the hotel and tourism sector from 2019 to 2022.
- The relationships of BDI with the temperature, alkalinity, and TSS were significant.

GRAPHICAL ABSTRACT



INTRODUCTION

Wastewater, containing a variety of pollutants, is generated on a large scale from residential, commercial, agricultural, and industrial activities (Sharma *et al.* 2022). However, accurately quantifying its amount and composition is challenging due to its diverse nature (Jones *et al.* 2021). Wastewater originates from both human settlements and industrial activities, with many industries in least developed countries discharging it untreated into the environment (Gbekley *et al.* 2023). Effective management and pollution control of wastewater is crucial for sustainable development, especially as water demand grows at twice the rate of population growth. To conserve water resources and reduce reliance on scarce freshwater, it is essential to implement strategies for wastewater production, treatment, and reuse (Abd-Elaty *et al.* 2021). Thus, there is a significant demand for water quality improvement in many industrial applications.

Reducing wastewater production can create jobs in a green economy, reduce operational costs, and reduce greenhouse gas emissions (Water Quality Standards & Wastewater 2015). Therefore, the monitoring of effluents offers the practical understanding required to make informed decisions regarding the management of water quality in both the present and the future. The practice of water quality monitoring serves the purpose of providing timely notification on prevailing, continuous, and emergent issues, as well as assessing adherence to established drinking water regulations and safeguarding the integrity of other advantageous water applications (Miller *et al.* 2023). The utilization of monitoring data in assessments aids legislators, water management professionals, and both government and non-government professionals in evaluating the efficacy of water policies, ascertaining trends in water quality improvement or deterioration, and devising novel policies to enhance the safeguarding of human health and the environment (Wolters & Steel 2021).

The process of controlling and reducing the release of pollutants into the environment is known as environmental pollution control and thus, the characterization of wastewater structures and the description of their sources hold significant importance in this context (Zhong & Peng 2021). The expansion of industrial pollution is constrained and controlled globally by effective environmental legislation. As a result of that, industries are required to establish pollution control strategies (Chapagain *et al.* 2022). The main concept of established pollution control strategies should be the methods that can be applied to combat pollution; however, these strategies should be profoundly evolved with the changing nature of pollutants.

Pollution prevention is preferred over treating pollution at its origin. Many scientists and institutions have developed wastewater quality indicators, methods used in laboratories to determine if wastewater is suitable for disposal, treatment, or reuse. Traditional physicochemical indicators are commonly recognized by the public as measures of water quality, including parameters like dissolved oxygen (DO), pH, temperature, salinity, and nutrients (specifically nitrogen and phosphorus) (Retnaningsih *et al.* 2023). Additionally, water quality assessment also includes metrics for harmful substances such as pesticides, herbicides, and metals (Renu Nayar 2020). These indicators provide insights into factors influencing the sustainability of water systems. For instance, they help determine whether organic waste is affecting DO levels or if a specific toxic substance is responsible. However, while physicochemical indicators can identify the source of pollution, they offer limited information on the impact of pollution on fauna and flora. Additionally, obtaining these measurements is time-consuming, limiting their potential for immediate online monitoring (Yang *et al.* 2014).

As a solution, the Environmental Protection License (EPL) in Sri Lanka serves as a regulatory mechanism for managing the discharge of effluents, waste deposition, and emission of smoke, gases, fumes, vapor, excessive noise, and vibration into the environment resulting from specific activities, thus the mechanisms used to deal with pollution require changing (CEA 2022). Prevention of water pollution is preferred over the end of the pipe treatment of pollution (CEA 2022). The use of a rapid, highly sensitive, and real-time monitoring tool can effectively ensure the reliability of wastewater treatment performance (Cassidy *et al.* 2023). For example, monitoring of organic matter in the effluents from wastewater treatment plants is substantially important to evaluate the influence of effluent discharge on the water quality, the biogeochemical processes, and the ecosystem functions of the receiving water (Park *et al.* 2022).

In both natural aquatic environments and industrial discharge, the process of oxidation occurs wherein any substance that is susceptible to oxidation undergoes chemical and biological (specifically bacterial) reactions. This leads to a consequential reduction in the oxygen content of the water (Bagheri *et al.* 2017). Within this particular framework, biological oxygen demand (BOD) denotes the quantification of oxygen utilized by bacteria during the process of organic matter decomposition, thereby serving as an indicator of the matter's capacity for biodegradation in aquatic environments. In contrast, chemical oxygen demand (COD) serves as a measure of the amount of DO necessary for the oxidation of chemical organic substances. The assessment of water pollution levels is important, as shown by numerous studies (Geerdink *et al.* 2017; Young & Lipták 2018), which highlight the significance of these measurements. In recent studies, the BOD/COD ratio has emerged as a prominent indicator for evaluating the biodegradability of total organic carbon (Boruah & Deka 2023). It functions as an indicator of the capacity of a waste contaminant to diminish the presence of oxygen. Moreover, previous studies have demonstrated the usefulness of the BOD:COD ratio as a predictive indicator for the correlation between BOD and COD, as well as for assessing the presence of organic substances in wastewater and industrial water (Andrio *et al.* 2019a, 2019b; Bader *et al.* 2022). Modifying this proportion, as exemplified in research pertaining to tofu wastewater and cow dung (Andrio *et al.* 2019a, 2019b), can contribute to informed decision-making regarding treatment technology and discharge regulations. A higher ratio of BOD to COD typically indicates reduced biodegradability, which has implications for the development of wastewater treatment strategies aimed at attaining acceptable levels of organic matter in the surrounding ecosystem (Lee & Nikraz 2014; Dhanke & Wagh 2020; Al-Rosyid *et al.* 2022).

The determination of BOD_5 (BOD_5 refers to the biological oxygen demand after 5 days of incubations) (Medvedev *et al.* 2023) and COD is often performed in analytical procedures in the assessment of wastewater (Aguilar-Torrejón *et al.* 2023). These measurements quantify the amount of organic matter that can undergo oxidation through chemical or biological processes (Nidheesh *et al.* 2021). They are strongly interrelated, making their combined use advisable. COD estimates are generally higher than BOD_5 and depend on the specific water sample being analyzed. The BOD_5 to COD ratio should not exceed 1.0 (Gutiérrez-Mosquera *et al.* 2022), indicating the fraction of biodegradable organic matter in wastewater. However, this ratio provides empirical, not absolute, results, and is useful for comparing different samples rather than quantifying specific pollutants.

Furthermore, BOD_5 and COD were designed to evaluate the impact of localized organic effluents on water sources, limiting their applicability for broader environmental monitoring. For instance, BOD can increase due to elevated nutrient levels (nitrogen and phosphorus) causing eutrophication, even without significant external organic carbon input. A key limitation of BOD_5 is the 5-day incubation period required for data collection (Yan *et al.* 2021). Furthermore, these methods do not accurately reflect *in situ* oxygen consumption rates due to artificial incubation conditions, such as lack of airflow, currents, and light, which differ from natural environmental factors.

However, despite the extensive breadth of this investigation, there are still certain areas of research that need to be further examined. The current body of research pertaining to the utilization of the BOD_5:COD ratio as an indicator for effluents originating from the hospitality and vehicle service sectors in the Matara District is notably scarce (Kumarathilaka *et al.* 2015). Hotel effluent contains various organic pollutants, including nutrients, pathogens, and chemicals, while vehicle washing center wastewater is characterized by dirt, oils, and other contaminants (Sharma & Sanghi 2012). Additionally, there is a lack of comprehensive research on the correlation between the BOD_5:COD ratio and other significant physicochemical parameters in these industries (Amarasinghe *et al.* 2017; Young *et al.* 2021). Therefore, a more detailed biodegradability index (BDI) is necessary to better understand water quality in terms of biodegradability. However, comprehensive comparative analyses of these industries within Sri Lanka's specific environmental conditions and regulatory frameworks are limited (Dissanayake *et al.* 2007; Kumara *et al.* 2015). Addressing these research gaps can enhance our understanding of effluent biodegradability in various industries and their impact on local water bodies, contributing to more effective environmental management strategies.

The present study focuses on the utilization of BDI as a matrix for assessing the effluents discharged by hotels and tourism establishments, as well as vehicle service stations, within the Matara District of Sri Lanka. In this light, we conducted this study with the objectives (1) to conduct a comparative analysis of BDI values among different industrial effluents and a reference site such as the Nilwala River, (2) to investigate the correlation between the aforementioned ratio and a range of physicochemical parameters, such as pH, temperature, electrical conductivity (EC), total suspended solids (TSS), alkalinity, and BDI of wastewater, within distinct industry categories, and (3) to conduct an analysis and identification of any notable disparities in the BDI between the effluents of the reference sites, specifically focusing on the pristine sites of Nilwala River as reference sites, and those originating from other industries within the surrounding area.

METHODOLOGY

Study area

The study was conducted in the Matara District along the Nilwala River, which is the third largest in the southern province of Sri Lanka covering a distance of 72 km (the area of the Nilwala River Basin is 922 km^2) (Jayawardana *et al.* 2016). The river originates at Panilkanda in the Sinharaja rainforest near Deniyaya at an altitude of 1,050 m and flows largely through urban, agricultural, and other areas of land use to join the Indian Ocean at Thotamuna (Jayawardana *et al.* 2016; Wickramarachchi & Wijesekera 2022). Nearly 90% of the area covered by the catchment of the Nilwala River belongs to the Matara District (Panditharathne *et al.* 2022). The area of the river basin is about 1,073 km^2. Nilwala River is the primary drinking water source to cover the water supply requirement in the Matara District (Chathuranika *et al.* 2022).

The Matara District is influenced by various industrial and tourism activities (Danthanarayana & Arachchi 2021). Hence, we selected eight sampling sites (sites 1–8) (Figure 1), at the main tributaries of the Nilwala River. The river water was used as a reference in our study due to its central role in the local ecosystem as the main supply source of drinking water to the Matara District in Sri Lanka (Diwyanjalee & Premarathne 2024).

Vehicle service centers, sawmills, and tanneries, as well as medium and small-scale industries, such as textile, batik, apparel, food processing industries, and restaurants and hotels are also located in the urban areas along the river (Abeysiriwardana & Wijesekera 2022). The lower reaches of the river run through a thriving commercial city, and its vast areas are rapidly changing land use and deforestation. The predominant type of land use in those areas is urban buildings such as cities and industries (Chathuranika *et al.* 2022).

Those industries are categorized into three lists based on their potential for pollution by the Central Environmental Authority (CEA), namely categories 'A', 'B' and 'C' (CEA 2023).

- Category 'A' consists of 80 significantly higher polluting industrial activities.
- Category 'B' consists of 33 intermediate levels of contaminant activity.
- Category 'C' consists of 25 less polluting industrial activities assigned to local authorities.

As a result, Matara District has 416 'A' category industries, 471 'B' category industries, and 1,327 'C' category industries including hotels, service centers, saw mills, tanneries, textile, batik, apparel, food processing, and painting industries. Therefore, the unavailability of BOD and COD ratios in different industry sectors can lead to time consumption and reduce the overall efficiency of CEA service.

Table 1 presents the details of the sampling points, categorized by type and their specific locations within the study area. Since small-scale vehicle washing centers are prominent in the river basin, we selected six vehicle

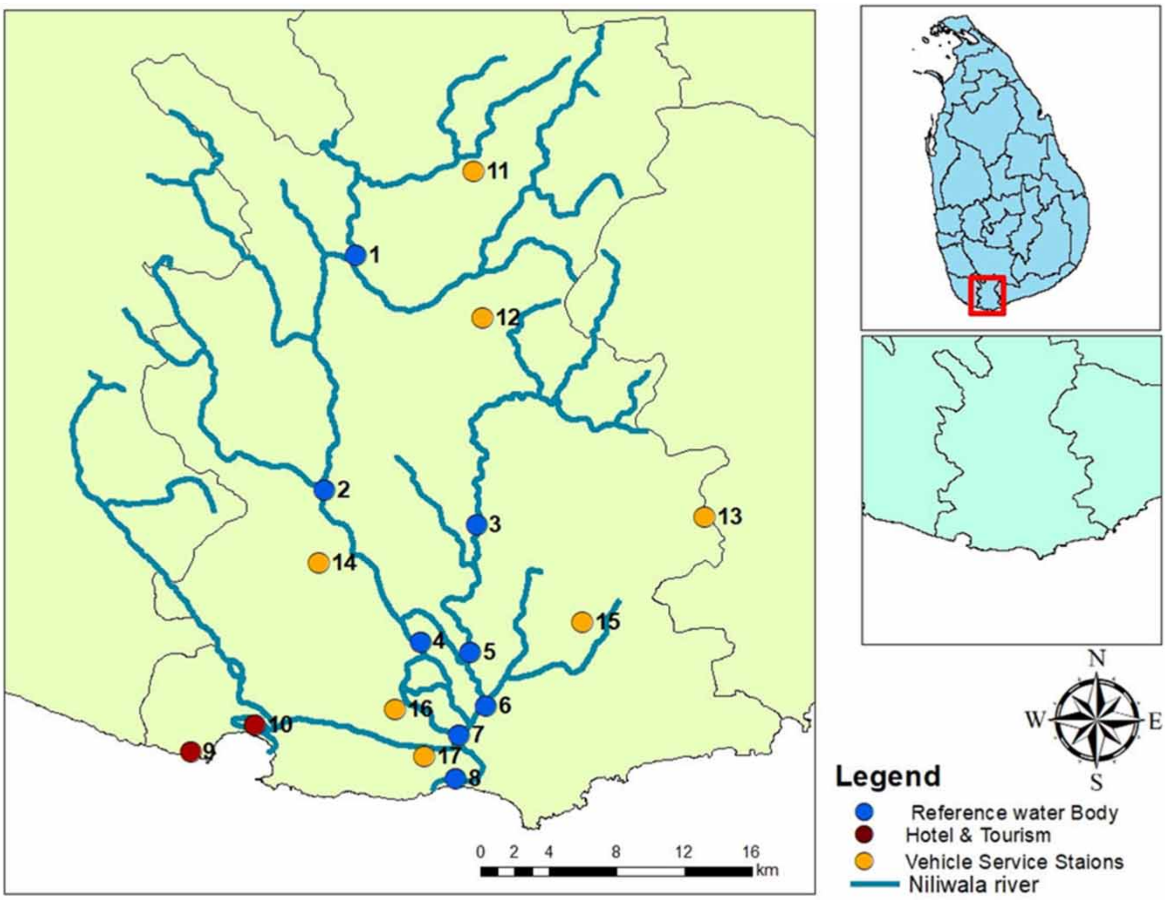


Figure 1 | Study area in the Matara District, highlighting sampling points for different categories: red color points for hotel and tourism industries, yellow color points for vehicle service stations, and blue points for locations along the reference water body.

Table 1 | Comprehensive overview of sampling sites in the Matara District

Sampling points	Category	Location
1	Reference water body	Uru Boku Aru
2	Reference water body	Akuressa
3	Reference water body	Sapugoda
4	Reference water body	Wellethota
5	Reference water body	Piththare
6	Reference water body	Bandaththara
7	Reference water body	Hungangoda
8	Reference water body	Matara
9	Hotel and tourism	Weligama
10	Hotel and tourism	Weligama
11	Vehicle service station	Kotapola
12	Vehicle service station	Pasgoda
13	Vehicle service station	Hakmana
14	Vehicle service station	Athuraliya
15	Vehicle service station	Thihagoda
16	Vehicle service station	Godagama
17	Vehicle service station	Matara

service stations (sites 11–17) as one of the selected industries and two tourist hotels (site 9 and site 10), were selected as another industrial category (Table 1).

Data collection

Effluent data used in this study were obtained from performance results of the above-mentioned sites in Matara District over seven years from 2015 to 2022. Sampling was done as mentioned in the standard methods for the examination of water and wastewater by the American Public Health Association (APHA) requirements (Bridgewater *et al.* 2017).

To conduct the laboratory testing for COD, BOD_5, and alkalinity, composite water samples from each sampling site were collected into 1.5 L glass sampling bottles, preserved on site, and transported to the CEA's water laboratory in Koggala, Galle District, Sri Lanka where they were stored at 4 °C temperature.

Sample analysis

BOD over 5 days (following Winkler's approach) and COD for each sample were measured in laboratory conditions.

At the sampling site, the temperature, pH, and EC characteristics were instantly determined by using a portable multi-parameter water quality analyzer (Horiba-U52) and TSS was determined for effluent samples from the industries while total alkalinity was determined for the water samples from a reference water body (Table 2).

Table 2 | Analyzed water quality parameters with standard methodologies

Parameter	Unit	Standard method
Temperature	°C	Thermometric APHA 2550 B
pH	–	Electrometric APHA 4500 $-H+B$
EC	µs/cm	Electrometric APHA 2510 B
COD	mg/L	Open Reflux Titrimetric APHA 5220 B
BOD_5	mg/L	Titrimetric APHA 5210 B
TSS	mg/L	APHA 2540 D
Alkalinity	mg/L	APHA 2320 B

Three replicates were used to test each parameter. Double-distilled water and chemicals of analytical quality were utilized in the analysis. All chemical and physical analyses were performed under ISO 17025 quality standards to prevent random and intentional measurement errors.

The BDI for each sample was calculated using the following equation:

$$\mathrm{BDI} = \frac{\mathrm{BOD}_5}{\mathrm{COD}} \tag{1}$$

The temperature, pH, EC, TSS, and total alkalinity were determined to analyze the relationship of these parameters with BDI.

Statistical analysis

Experimental results were statistically analyzed using one-way ANOVA, Mann–Kendall trend analysis, and multiple linear regressions. One-way ANOVA (Tukey's pairwise test) at a 5% significance level was conducted to investigate the significant difference between the BDI of the natural water body (reference) and other industry sectors. Before analysis, the data were assessed for normality and homogeneity of variance using IBM SPSS 26.0 software using the Anderson Darling's test.

The time series BDI was plotted to understand the temporal variation (diurnal and seasonal variations) of the BDI with time in each industrial setting by using approximately 150 samples. Further, the Mann–Kendall trend analysis was conducted to predict whether the BDI is significant with time in each selected site category (reference water body, hotel and tourism, and vehicle service stations).

Finally, the regression analysis with some common parameters (pH, temperature, TSS, and EC) was conducted to understand the relationship of the BDI with other physicochemical parameters.

RESULTS

The spatial changes of BDI in various industrial settings and reference water body, Nilwala River in the Matara District, are illustrated in Figure 2. It provides a visual summary of the distribution of data, central tendency, and variability. The interquartile range (IQR) for Industry 9 (hotel and tourism) is 0.3476059 ($Q1 = 1.32$, $Q3 = 1.58$), indicating slightly higher variability compared to other industries, while sampling point 11 (a vehicle washing station) showing less variability compared to the other industries ($IQR = 0.104205$). Outliers are indicated by points outside the whiskers (Figure 2(b)). Sampling point 6 (a reference site) has several outliers, suggesting

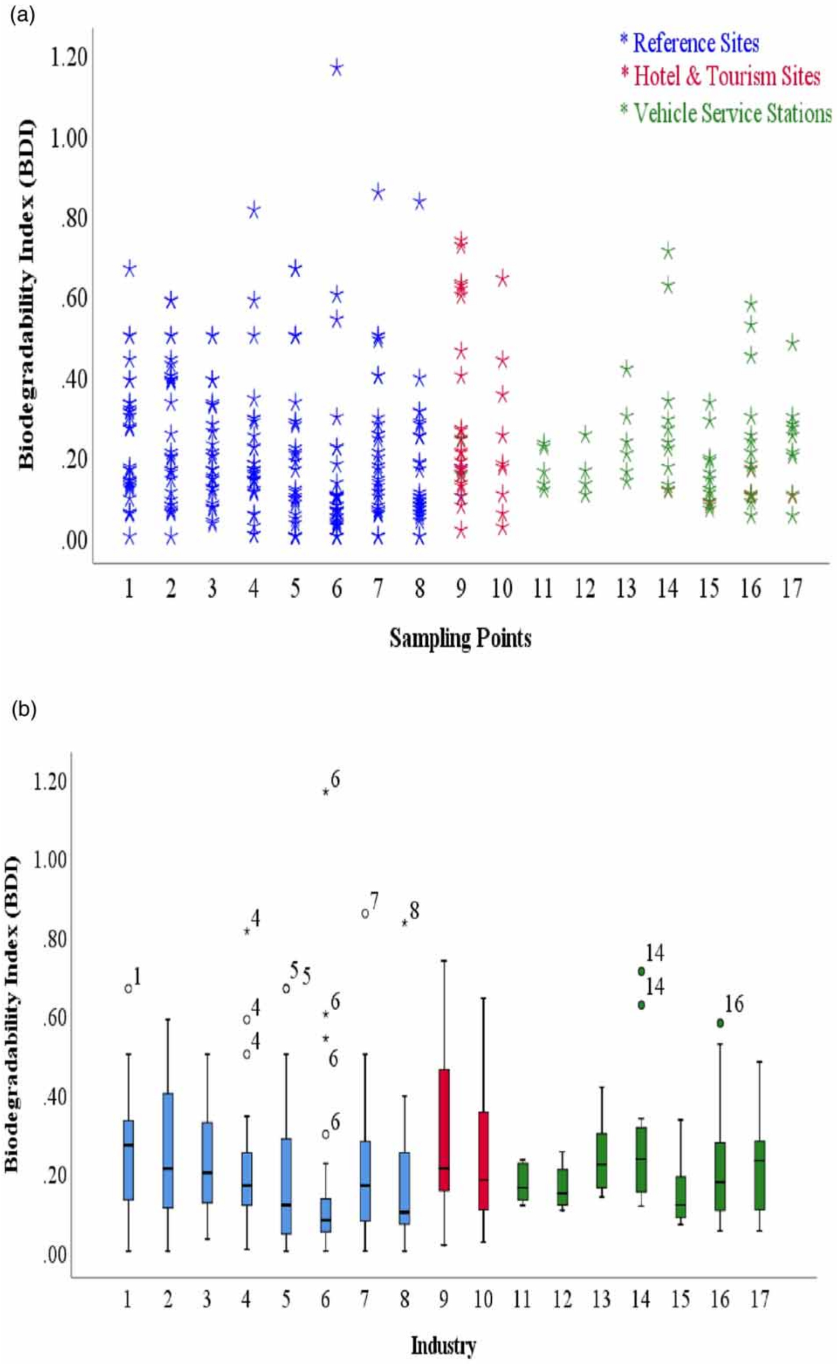


Figure 2 | (a) Distribution of biodegradability index (BDI) from 2015 to 2022 at selected sites in the Matara District. (b) BDI values represent the monthly average, across multiple industries in the Matara District from 2015 to 2022. Each color represents a different industry/site. Outliers indicate significant deviations in biodegradability. Blue: reference water body, Red: hotel and tourism, Green: vehicle washing centers.

occasional extreme values. Therefore, the boxplot effectively highlights the differences in BDI values across two selected industrial settings and reference waterbody, Nilwala River in the Matara District. Site 1 at the reference water body consistently shows the highest biodegradability (the highest median BDI value = 0.2695), while site 6 has the smallest median BDI value (0.0784).

It indicates that BDI in a significant number of sites is below the ideal BDI value for ready biodegradability (0.4). However, the majority of the BDI in the Nilwala River is ranged from 0.2 to 0.5 while the BDI of hotels and tourism industries and vehicle washing centers range from 0.2 to 0.48 (Figure 2(a)).

Spatial variation of BDI across selected industries

As per the one-way ANOVA test results, the findings demonstrated significant differences between the BDI values of 17 sampling sites including reference water bodies, hotel and tourism industries, and vehicle service stations within the study period ($p > 0.05$). The highest mean BDI value was recorded in site 9 (hotel No: 1), followed by site 10 (hotel No: 2), and the least mean BDI value was recorded from site 6 (a site of reference water body) (Figure 3).

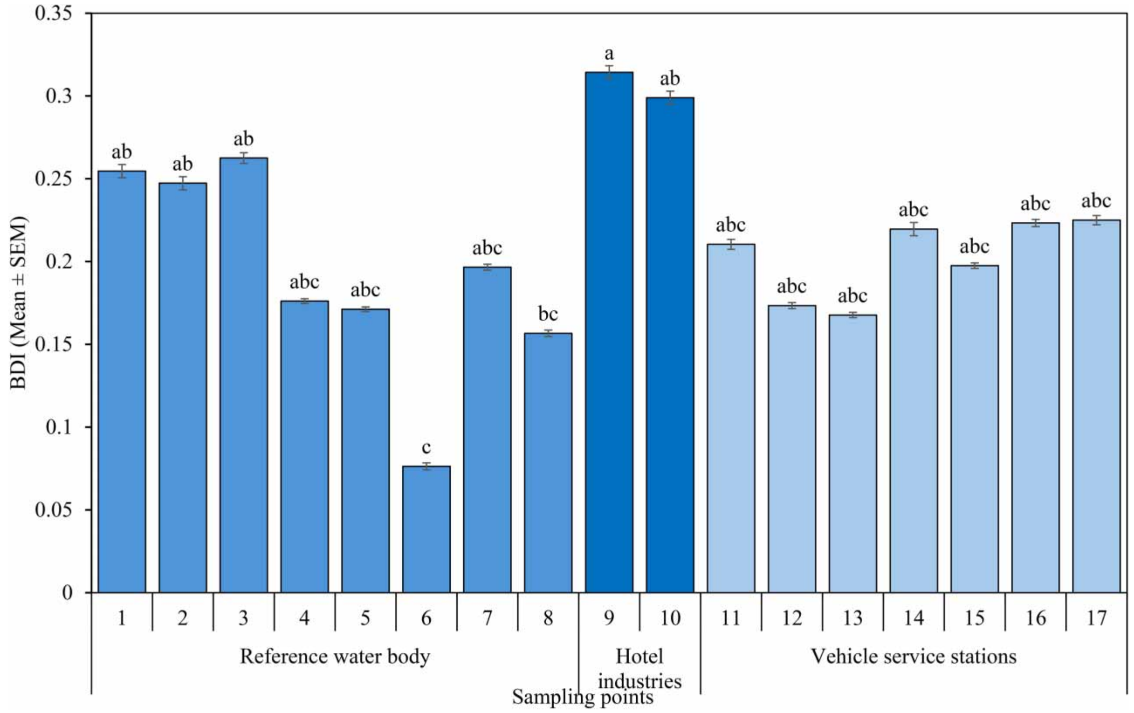


Figure 3 | Spatial variation of biodegradability in 17 sampling points from different industries; sites 1–8, reference sites (Nilwala river); site 9 and site 10, hotel and tourism; sites 11–17, vehicle service stations.

Temporal variation of BDI among selected industries

The temporal variation of the BDI among the selected wastewater industries in the Matara District is illustrated in Figure 4. There was no significant temporal variation between the BDI values of different industry categories within the study period from 2015 to 2022 ($p > 0.05$).

To identify similarities in BOD:COD ratios between months and determine the months with the highest and lowest variation throughout the period, the coefficient of variation (CV) for each month was calculated by considering the monthly average BDI from 2015 to 2022 (Table 3). The CV considers the standard deviation relative to the mean and can give us an indication of the relative variation in the ratios.

Trend analysis of BDI

In this study, Mann–Kendall was used for the analysis of trends in the BDI for the period from 2019 to 2022 for different industrial categories. The trend is considered statistically significant at a 0.05 confidence level. There is a downward trend in the data (Table 4).

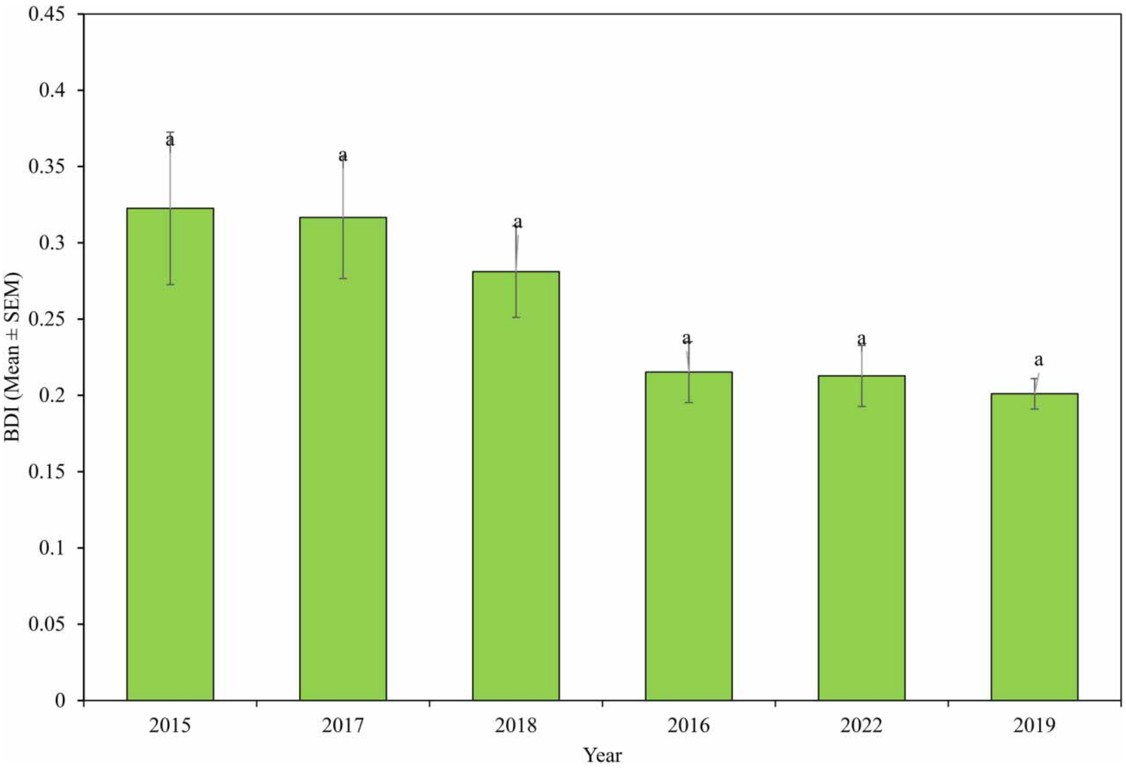


Figure 4 | Temporal variation of BDI in 17 sampling points from different industries from 2015 to 2022.

Table 3 | Temporal variations of average BDI in different industrial settings and reference sites (reference waterbody, vehicle service stations, hotel and tourism industries) from 2015 to 2022 using CV)

	Reference waterbody		**Vehicle service stations**		**Hotel and tourism industries**	
Month	**Coefficient of variation (CV) (%)**	**Average BDI**	**Coefficient of variation (CV) (%)**	**Average BDI**	**Coefficient of variation (CV) (%)**	**Average BDI**
Jan	10.4	0.404	65.6	0.366	58.5	0.368
Feb	16.4	0.441	44.5	0.221	69.8	0.221
Mar	33.5	0.174	41.6	0.259	39.5	0.293
Apr	17.1	0.197	57.2	0.138	78.3	0.138
May	21.5	0.179	41.8	0.157	20.8	0.139
Jun	25.4	0.180	33.9	0.263	58.7	0.256
Jul	25.9	0.205	38.1	0.177	18.2	0.143
Aug	14.5	0.235	29.9	0.356	59.7	0.355
Sep	82.5	0.203	49.8	0.288	36.8	0.323
Oct	76.6	0.245	50.5	0.325	31.6	0.291
Nov	45.7	0.319	38.7	0.311	28.9	0.313
Dec	51.2	0.381	29.0	0.230	79.9	0.231

Based on the CV values, it presents highly variable differences in the biodegradability ratios during the months over the years.

The Mann–Kendall trend analysis concludes that there is no significant evidence of either an upward or a downward trend for the BDI values of the reference water body (Nilwala River) and 'vehicle service station' category at a significance level of 0.05. However, based on the Mann–Kendall trend test using normal approximation, there is evidence of an upward trend in the 'hotel and tourism industries' data with time at a significance level of 0.05 (Table 4).

Table 4 | Mann–Kendall results for different industrial categories

Industry category	Calculated *z*	*p*-value for the upward trend	*p*-value for the downward trend
Reference water body	1.04883	0.147128	0.852872
Hotel and tourism industries	2.00264	0.0226078	0.977392
Vehicle service stations	0.939842	0.173649	0.826351

Significance level (α) = 0.05.

The regression equations indicate varying trends in the BOD:COD ratios over time across different water use categories, though all models exhibit low predictive power (Figure 5). For natural water, the ratio is expected to decrease slightly over time (BOD:COD = 0.2922–0.00406 × month), but the low R^2 value suggests significant influence from other factors. In the hotel and tourism category, the ratio shows a slight increase over time, with an R^2 value of 0.0813 indicating that time explains only 8.13% of the variability, pointing to other influential factors. Similarly, for vehicle washing stations, the BOD:COD ratio shows a minimal upward trend (coefficient of 0.00044) with an R^2 of 0.0021, again suggesting that other factors are more impactful in determining the ratio (Table 5).

Correlation of BDI with other parameters in different industries

A multiple linear regression analysis using the enter method was conducted to examine the relationship of the BDI with other physicochemical parameters (pH, temperature, TSS, conductivity, and alkalinity) in different

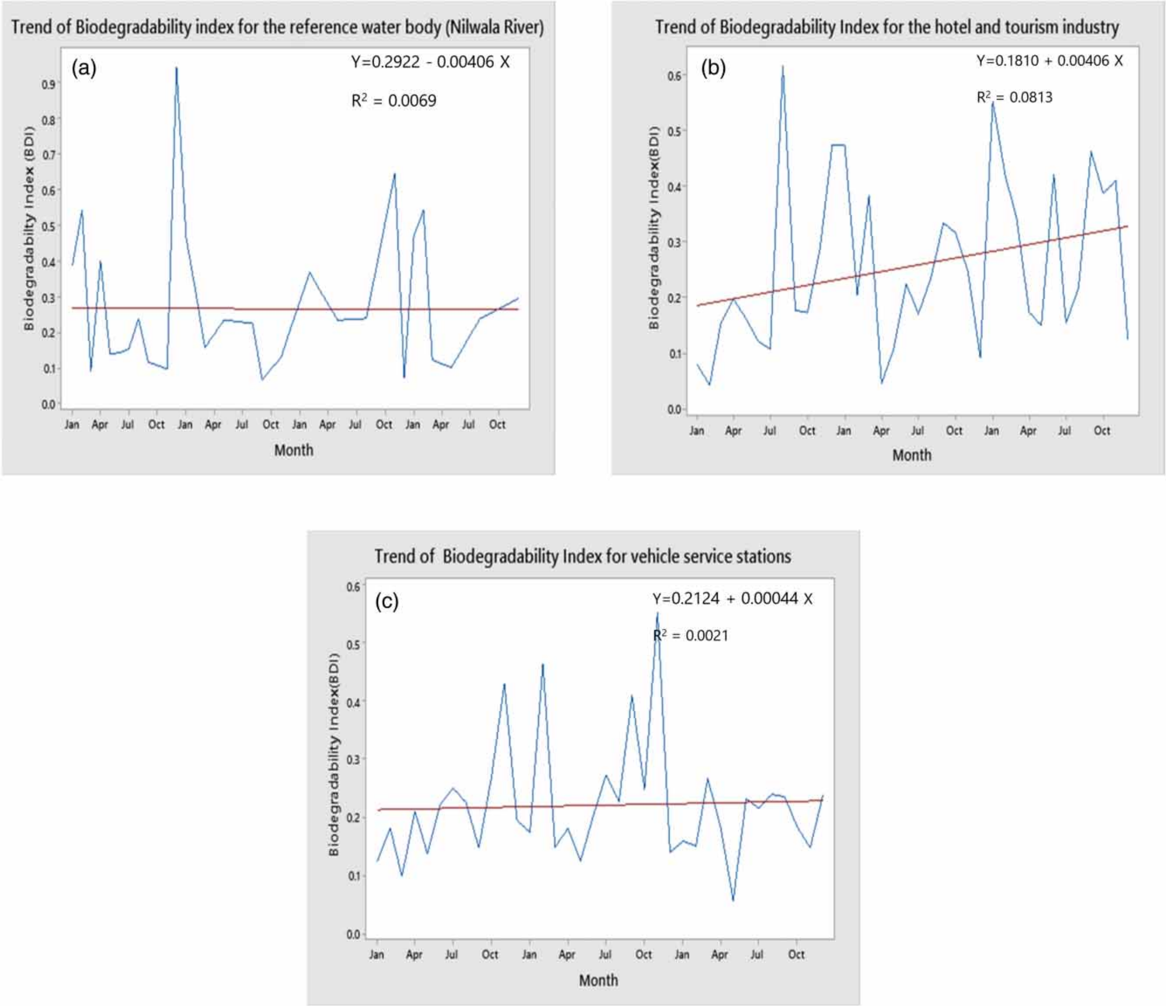


Figure 5 | Trends of BDI in different industry sectors. (a) Reference water bodies, (b) hotel and tourism industries, and (c) vehicle service stations.

Table 5 | Correlations and ANOVA summary data

						ANOVA	
Predictors	***R***	***R*²**	**Adjusted *R*²**	**Std. error of the estimate**	***R*² change**	***F***	***p*-value**
pH	0.060[a]	0.004	−0.001	0.2496	0.004	0.84	0.432[b]
Temperature	0.106[a]	0.011	0.007	0.24866	0.011	3.637	0.043[b]
EC	0.085[a]	0.007	0.003	0.24914	0.007	1.683	0.187[b]
Alkalinity	0.141[a]	0.02	0.016	0.28876	0.02	4.653	0.032[b]
TSS	0.251[a]	0.063	0.055	0.19411	0.063	7.663	0.001[b]

[a] Predictors.

[b] Dependent variable: BDI.

industry categories. Temperature, $F\ (2, 460) = 3.637$, $p = 0.043$, alkalinity $F\ (1, 229) = 4.653$, $p = 0.032$, and TSS $F\ (2, 228) = 7.663$, $p = 0.001$, were significant by explaining 1.1% ($R^2 = 0.011$), 2% ($R^2 = 0.02$), and 6.3% ($R^2 = 0.063$) of the variance in the outcome variables, respectively (Table 4). pH ($B = -0.011$, $t = -1.947$), alkalinity ($B = -0.002$, $t = -2.157$), and TSS ($B = -0.001$, $t = -3.027$) contributed significantly to BDI (Supplementary material, Table S2).

Figure 6 depicts the correlations of temperature, pH, EC, alkalinity, and TSS to BOD:COD ratio (BDI) of water at a 95% confidence level. Here, the residual value, E, which is the difference between the actual outcome and the expected outcome, is accounted for by such slide variations.

DISCUSSION

This comprehensive analysis aims to provide a thorough examination of recent research findings pertaining to the variation of BDI in diverse industries. It explores the spatial and temporal dimensions of BDI, identifies emerging trends, and investigates the correlation between BDI and various parameters. The objective is to facilitate a comprehensive understanding of the biodegradability of waste materials in the Matara District.

Spatial variation of BDI across selected industries

In the present study, between 2015 and 2022, the BDI in the Nilwala River ranged from 0.1 to 0.7, while the BDI of hotels and tourism ranged from 0.1 to 0.75, and the BDI of vehicle washing centers ranged from 0.05 to 0.71. However, the previous studies conducted by Samudro & Mangkoedihardjo (2020) and Chandra & Singh (2012) found that BDI > 0.5 indicated high biodegradability. Furthermore, Ghauch *et al.* (2018) reported that BDI between 0.2 and 0.5 indicates moderate biodegradability during Congo red dye degradation under different conditions. Conversely, some other studies asserted that BDI can be as low as <0.2 (Velicu & Yamamoto 2011); BDI around 0.35 (Rudaru *et al.* 2022); and BDI > 0.4 (Lee & Nikraz 2014). The results of the present study correspond to the published literature, as they showed a BDI ranging from low to high biodegradability among the sampling points represented by different industries.

Moreover, the one-way ANOVA test results show significant differences between the BDI values of 17 sampling sites, with site 9 and site 10 (hotels and tourism) recording the highest mean BDI value and site 6 (reference water body) recording the lowest mean BDI value. Given the significance of natural organic matter's biodegradability, we found that natural water bodies typically contain more biodegradable natural organic matter than industrial effluents. Furthermore, studies have shown that seasonal variations and anthropogenic activities can also influence its BDI (Houghton & Quarmby 1999; Haider *et al.* 2018). During both the dry and rainy seasons, a past study on the Nilwala River confirmed that sampling site 6 (Bandaththara power plant) and site 8 (Matara Mahanama Bridge) have a higher weighted arithmetic water quality index (WAWQI). Moreover, the same study showed that some sampling points in the Nilwala River are suitable for drinking even during the dry season (Diwyanjalee & Premarathne 2024). Therefore, the BDI in natural water bodies represents a complex interplay of molecular structure and complexity (Houghton & Quarmby 1999), concentration, and composition (Thakur 2006). This study examined various industrial sites and discovered that they had lower-than-optimal biodegradability ratios. Higher levels of organic matter are likely to be present, which could stop biodegradation from happening properly and lead to possible toxic risks (Papadopoulos *et al.* 2001; Andrio *et al.* 2019a, 2019b).

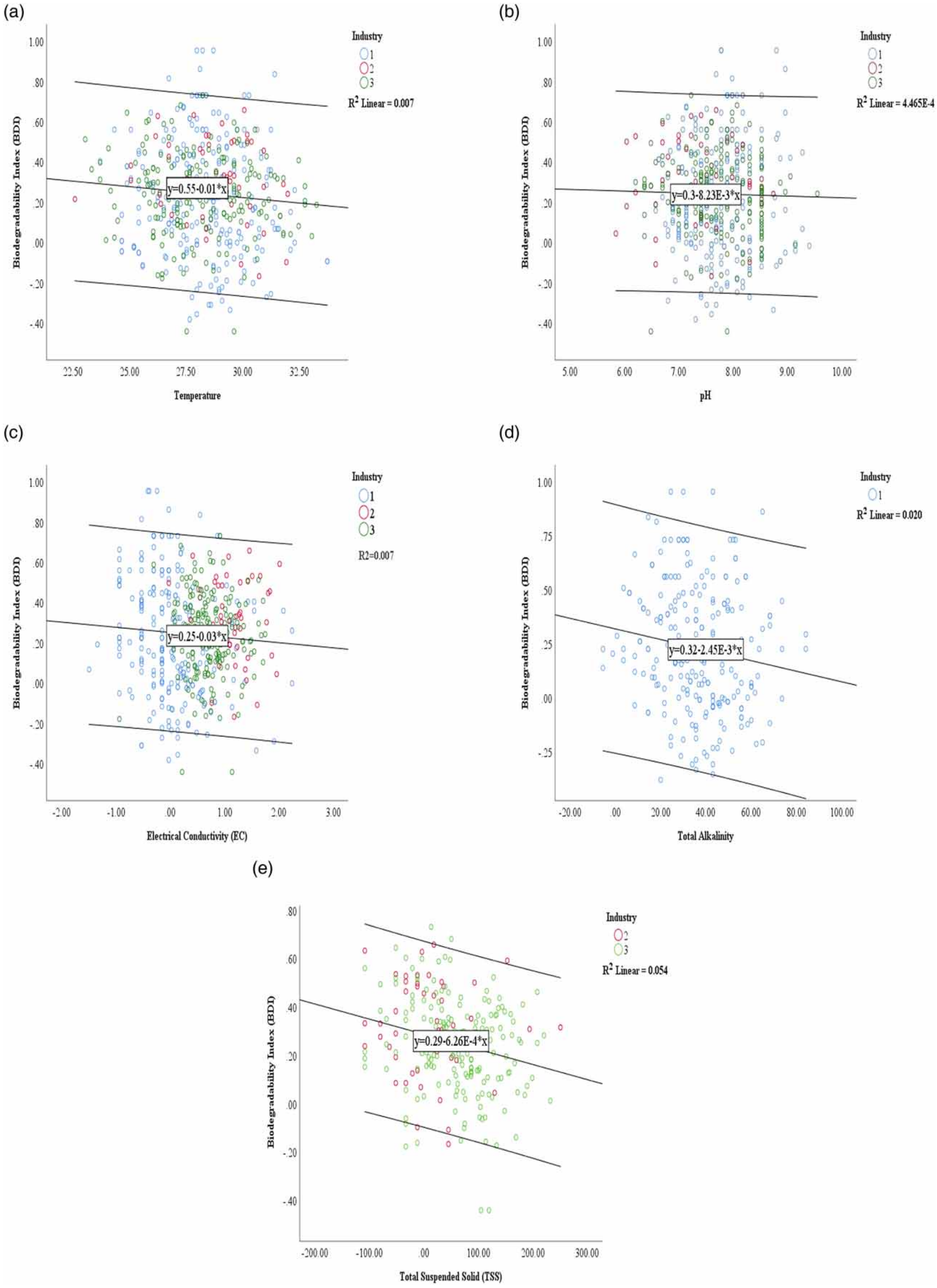


Figure 6 | Correlations between BDI and other water quality parameters. (a) Temperature, (b) pH, (c) EC, (d) total alkalinity, and (e) TSS.

Moreover, it is worth noting that the hotel and tourism industries exhibited the highest BDI values, as illustrated in Figure 3. The elevated levels of organic matter in sewage waste contribute to a greater BOD due to the proliferation of a more extensive microorganism population (Mtui 2001). A combination of organic matter characteristics, environmental conditions, microbial community dynamics, nutrient availability, inhibitory substances, operational practices, and seasonal variations affect the BDI in wastewater from hotel and tourism effluents. Nies (1999) conducted a previous study which revealed that certain cleaning agents, disinfectants, and personal care products may contain compounds that inhibit microbial activity, thereby reducing biodegradability. Henze *et al.* (2008) found that hotels with advanced pretreatment systems, including pretreatment, can significantly affect the higher BDI as they reduce toxic loads and produce more balanced organic matter. Furthermore, peak tourist seasons can result in higher volumes of wastewater with varying organic loads, affecting the BDI. During off-peak times, wastewater composition and volume may change, influencing biodegradability (Gössling 2002). The selected hotels in the present study maintain a relatively constant tourist attraction, as they cater to both local and foreign tourists annually. As a result, local celebrations, gatherings, and check-ins are common during off-season foreign tourist seasons.

Temporal variation of BDI among selected industries

The outcomes from the ANOVA indicated that there was no statistically significant temporal variation in the BDI scores among the various industries. This insignificant temporal variation can be related to several factors driven by the nature of industrial operations and wastewater management practices. Many industries function with highly standardized and controlled production processes, resulting in consistent wastewater composition over time (Metcalf & Eddy 2014). This uniformity is further proved by regular supply chains, which lead to consistency in the types and concentrations of organic compounds in the wastewater, thereby reducing variability in the BDI (Henze *et al.* 2008).

Pretreatment systems, designed to stabilize wastewater composition, also play a crucial role in minimizing temporal variations in BDI (Tchobanoglous *et al.* 2003). Industrial operations are frequently required to comply with stringent environmental standards that dictate the maintenance of a consistent standard of wastewater quality. Adherence to these rules requires consistent monitoring and management of wastewater parameters, such as BDI. In their study, Davis & Masten (2013) found that numerous industries maintain stable production cycles, resulting in predictable patterns of wastewater creation. Continuous operations in industries result in reduced temporal variability in effluent properties, unlike businesses that are seasonal in nature.

The employing of equalization tanks in industrial wastewater treatment systems supports homogenizing wastewater by mixing it, hence averaging out any fluctuations in the concentration of pollutants and organic matter. This is responsible for more consistent BDI (Tchobanoglous *et al.* 2003). Additionally, the consistent use of chemicals with standardized formulations and dosages leads to predictable and stable effluent characteristics (Thakur 2006). In contrast, the Nilwala River, a natural tropical water body, does not show statistically significant temporal variation in the BDI. This stability can be related to several environmental factors. The region's stable climatic conditions (Horne & Goldman 1994), continuous organic matter input from evergreen vegetation (Wetzel 2001), and consistent hydrological patterns (Ogden & Thorpe 2002) contribute to this stability. Furthermore, stable pH and DO levels (Kalff 2002), diverse and active microbial communities (Rittmann & McCarty 2001), and adequate nutrient availability (Thakur 2006) support consistent biodegradation rates. Limited seasonal variability in human activity (GESAMP 2001) and the natural buffering capacity of tropical ecosystems also play significant roles (Wetzel 2001).

The Mann–Kendall trend analysis depicted extremely low R^2 values, indicating that factors other than time are likely more important in determining the BDI. The Mann–Kendall trend test further shows that the BDI for most industrial categories remains stable over time. Nonetheless, an increasing trend in the hotel and tourism industries suggests an improvement in effluent quality, possibly due to enhanced wastewater management practices.

Correlation of BDI with other physicochemical parameters in selected industries

The regression coefficients indicate significant negative contributions of pH ($B = -0.011$, $t = -1.947$), alkalinity ($B = -0.002$, $t = -2.157$), and TSS ($B = -0.001$, $t = -3.027$) to the BDI. This suggests that as pH, alkalinity, and TSS increase, the BDI decreases. These findings align with previous studies and contribute to a broader understanding of the factors influencing biodegradability in aquatic environments. Previous research by Thakur (2006) demonstrated that BDI tends to increase with higher levels of DO because adequate oxygen levels support aerobic microbial activity, enhancing the biodegradation of organic matter. This is crucial as aerobic conditions generally favor a higher rate of organic matter breakdown, leading to an increase in BDI. Similarly, Lim *et al.* (2001) found that higher temperatures generally boost microbial metabolism and enzymatic activity, which can also lead to higher BDI values. However, it is important to note that extremely high temperatures can inhibit microbial activity, as highlighted by Wetzel (2001).

Moreover, the BDI is optimal within a neutral pH range (6.5–7.5). Henze *et al.* (2008) noted that extreme pH levels, whether acidic or alkaline, can inhibit microbial activity, thus reducing the BDI. This aligns with the present study's findings that increased pH negatively impacts BDI. Furthermore, Metcalf & Eddy (2014) emphasized the necessity of adequate nutrient levels, such as nitrogen and phosphorus, for microbial growth and activity, leading to higher BDI values. However, excessive nutrients can cause eutrophication, altering microbial dynamics and potentially reducing biodegradability.

High levels of suspended solids and turbidity can have dual effects on BDI. On one hand, they can block light and reduce oxygen levels, inhibiting microbial activity and lowering BDI. On the other hand, some suspended solids can provide a substrate for microbial attachment, aiding biodegradation, as noted by Tchobanoglous *et al.* (2003). Additionally, Davis & Masten (2013) highlighted that turbidity potentially leads to a higher BDI if the organic material is biodegradable.

Lee & Nikraz (2014) discovered that pH, hardness, TSS, and conductivity show strong positive relationships with biodegradability, whereas chloride and alkalinity show strong negative relationships. This reinforces the findings of the present study, where increased alkalinity was associated with decreased BDI. The multiple linear regression analysis further highlighted the significant influence of pH, alkalinity, and TSS on the BDI, corroborating the findings of Agarwal & Saxena (2011), who found that high alkalinity is associated with increased COD and decreased biochemical oxygen demand (BOD):COD ratios. Lim *et al.* (2001) also identified temperature as a factor enhancing both BOD and biodegradability.

Environmental conditions such as temperature (Rittmann & McCarty 2001), pH (Tchobanoglous *et al.* 2003), and DO (Metcalf & Eddy 2014) are critical factors influencing biodegradability. Additionally, microbial dynamics (Rittmann & McCarty 2001), nutrient availability (Thakur 2006), physical factors including exposure to sunlight (Velicu & Yamamoto 2011), water flow and mixing (Tchobanoglous *et al.* 2003), and the presence of inhibitory substances (Nies 1999) also play significant roles. Understanding these factors is crucial for assessing the biodegradability of pollutants and the overall health of aquatic ecosystems.

CONCLUSION

A significant spatial variation of BDI can be observed among different sampling sites including natural water bodies, vehicle service stations and hotel and tourism industries. Site 6 (Bandaththara of reference water body) showed the lowest level of BDI which is significantly different from site 9 (hotel 1), it could be difficult to biodegrade as well. The highest BDI is recorded at site 9. A BOD:COD ratio greater than 0.4 signifies the presence of water that is readily biodegradable. The study found that these sites exhibited lower than optimal biodegradability ratios, indicating the presence of higher concentrations of organic matter, which could hinder effective biodegradation and consequently give rise to potential toxic risks. The hotel and tourism industry exhibited the highest BDI values, attributed to elevated levels of organic matter present in sewage waste.

The absence of significant temporal variation in BDI indicates stability in water quality over time, underscoring the importance of consistent wastewater treatment efforts. The Mann–Kendall test's findings further validate these observations, suggesting that temporal changes in BDI values across the industry categories have not shown significant trends over the studied period. The low R^2 values indicate that the linear relationship between time and the BOD:COD ratio is very weak. This implies that factors other than time are likely playing a significant role in determining the BOD:COD ratio.

The Mann–Kendall trend test confirms that the BDI for most industrial categories remains stable over time. However, an increasing trend in the hotel and tourism industries suggests an improvement in effluent quality, possibly due to improved wastewater management practices.

The significant correlation between BDI and parameters such as temperature, alkalinity, and TSS indicates that these factors influence the biodegradability of effluents. This highlights the need to consider a range of physicochemical parameters in effluent quality assessments. However, decompositions are taking place in the water and can be taken as an indicator of the degradation of organic matter in wastewater. It can be provided as useful information for the design and management of effluent discharge that makes prediction more realistic for future trends.

RESEARCH LIMITATIONS AND FUTURE RESEARCH DIRECTIVES

Currently, there is a lack of regular monthly effluent analysis conducted in vehicle service centers, hotels, and the tourism industries, with the exception of the Nilwala River, which serves as a reference water body. The presence of more frequent data could have led to more promising results. Based on the findings derived from this study, the subsequent recommendations are put forth for careful consideration. The discharges in the reference river undergo changes as a result of the expansion of industrial and commercial activities, as well as the subsequent increase in population. These changes primarily stem from the non-point sources of pollutants being emitted. Hence, it is imperative to implement ongoing monitoring protocols in order to evaluate the quality of water. Furthermore, it is imperative to augment the frequency of industrial-level inspections regularly and frequently to ascertain the methods employed for waste water disposal and evaluate their suitability.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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