

Research Article

Development of a Biodegradability Index for Urban Rivers Using Detergent Concentration: A Case Study from Tehran, Iran

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Abstract

Urban rivers are increasingly impacted by anthropogenic activities, leading to significant changes in water quality and pollutant levels. These rivers are subject to multiple environmental pressures, such as industrial discharge, urban runoff, and domestic wastewater, all of which affect the ecological health of the water systems and surrounding communities. To assess the impacts of these pollutants and to guide appropriate water management strategies, reliable and efficient indicators are required. This study introduces a novel Biodegradability Index (BI) designed specifically for urban rivers, based on the ratio of Biochemical Oxygen Demand (BOD₅) to Chemical Oxygen Demand (COD). The proposed BI allows for better monitoring and management of organic pollution by considering the biodegradability of pollutants, which is an important factor in assessing a water body's self-purification potential. The index was developed using water samples collected across the metropolitan area of Tehran, Iran, and the relationship between the BI and various water quality variables (WQVs) was explored using statistical and machine learning techniques. The results show a strong correlation between detergent concentrations and the BI, with a Spearman correlation coefficient of 0.82 and an R^2 value of 0.63. A predictive model for BI was also developed using detergent concentrations, achieving an R^2 of 0.7, thus suggesting that detergent levels can serve as a reliable, low-cost predictor of biodegradability in urban rivers. This study offers a practical approach to estimating the BI, which could significantly improve water quality assessments in urban areas by providing a simpler and faster method for evaluating river health. The findings underscore the importance of using a dedicated biodegradability index tailored to urban rivers, which are subject to unique and complex pollutant profiles compared to natural water systems. The proposed method has potential applications for sustainable urban river management and pollution mitigation strategies.

Keywords

Urban Rivers, Biodegradability Index (BI), BOD₅/COD, Water Quality, Detergents, Machine Learning, SHAP, Random Forest, Tehran

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1. Introduction

Rivers are among the most vital surface water resources [1], playing a crucial role in supporting urban development and sustaining human life. Historically, many cities have been established near rivers to secure reliable access to water for drinking, agriculture, sanitation, and other essential needs [2]. In urban environments, the health of river systems is directly linked to public well-being, making regular monitoring of water quality imperative [3]. Water pollution in these rivers can lead to a wide range of adverse health outcomes [4] and negatively affect the overall quality of life in surrounding communities.

River water quality can be assessed through a variety of monitoring approaches that involve different physical, chemical, and biological indicators [5], each reflecting specific types of environmental stress. For instance, elevated concentrations of nitrogen compounds and fecal coliform bacteria often signify contamination from agricultural runoff and the use of nitrate-based fertilizers [6]. In addition to individual parameters, several composite indices are commonly used to evaluate overall water quality, such as the Water Quality Index (WQI) [7], the reaeration coefficient (K_2) [8], and the Biodegradability Index (BI) [9]. Each of these indices is suited to particular conditions and can provide valuable insights to support informed decision-making regarding aquatic ecosystem health and water resource management.

Biodegradability refers to the ability of organic substances to be broken down (decomposed) by microorganisms [10], such as bacteria and fungi, into simpler, non-toxic substances like water, carbon dioxide, and biomass [11]. In the context of water quality, BI is an important indicator of how easily organic pollutants in a water body can be decomposed by natural biological processes [12]. It helps assess the potential for self-purification [13] of rivers and streams.

BI can be calculated using various ratios, such as ratio of biochemical oxygen demand to total organic carbon (BOD_5/TOC) [14], chemical oxygen demand to total organic carbon (COD/TOC) [15], biochemical oxygen demand to total nitrogen (BOD_5/TN) [16], biochemical oxygen demand to total phosphorus (BOD_5/TP) [17], and most commonly, biochemical oxygen demand to chemical oxygen demand (BOD_5/COD) [18]. The BI value varies depending on the type of environment and wastewater source, but it generally falls within a defined range that aids scientists and policymakers in assessing organic pollution levels and treatment needs. For example, BI values differ based on the origin of the wastewater: medical center effluents typically have a BI of around 0.3 [19], while wastewater from the tourism and pharmaceutical industries may reach 0.4 [20]. The index also varies across water resources, with reported values of 1.561 for groundwater [21] and 0.22 for rivers [22]. These differences reflect the nature and biodegradability of organic matter present in each context.

Although several studies have reported BI values for rivers,

there remains a significant gap in understanding and evaluating BI specifically in urban rivers. Urban water bodies are subject to numerous anthropogenic pressures [23] that are less prevalent in more pristine, natural river systems. Activities such as transportation, food production, industrial discharge, and domestic wastewater input create a complex and dynamic environmental setting in urban areas. These stressors can significantly influence the composition and biodegradability of organic matter, potentially altering BI values. Therefore, there is a need to investigate and establish BI values tailored to the unique conditions of urban rivers, to support accurate water quality assessments and informed decision-making [24].

In this study, a new BI specific to urban river water is proposed, based on the BOD_5/COD ratio. The research further investigates the influence of various water quality variables (WQVs) on this index [25]. Several analytical and machine learning techniques, including SHAP (SHapley Additive exPlanations), Random Forest Regression [26], and clustering algorithms [27], were employed to identify the most significant factors affecting BI. Finally, an empirical equation is introduced to enable rapid and cost-effective prediction of BI values, contributing to more efficient urban water quality monitoring and management.

2. Materials and Methods

2.1. Study Area

Tehran, the capital of Iran, is situated in the north-central region of the country, at approximately 35°41'46"N latitude and 51°25'23"E longitude (Figure 1). As the most populous city in Western Asia, it hosts over 8 million residents within the city limits and approximately 15 million in its greater metropolitan area. Spanning an area of nearly 730 square kilometers, Tehran is not only one of the largest cities in the region but also a major political, economic, and cultural hub [28].

The city's climate is classified as semi-arid with continental influences, characterized by hot, dry summers and cold winters. Tehran receives an average annual rainfall of about 228 millimeters, with the majority of precipitation occurring during the winter months. This climate regime, coupled with seasonal variability in precipitation, significantly influences the hydrological behavior of the city's water systems.

Tehran's topography is highly diverse, ranging from low-lying, flat areas in the south to elevated, mountainous terrain in the north. This variation has a notable impact on both urban development patterns and surface water hydrology [29]. Land use in Tehran reflects a heterogeneous mix of residential, commercial, and industrial zones, shaped by rapid urban expansion over recent decades. This urbanization has

led to significant land use changes and increased pressure on the city's natural resources, particularly its rivers.

From a hydrological perspective, Tehran can be divided into three main drainage zones based on its topographic configuration: eastern, central, and western tributary catchments. These urban tributaries collectively drain into a primary col-

lector system located in the southern part of the city. This drainage network is critical for managing surface runoff and water quality within Tehran's urban ecosystem, especially in the context of increasing urban pressures and climatic variability.

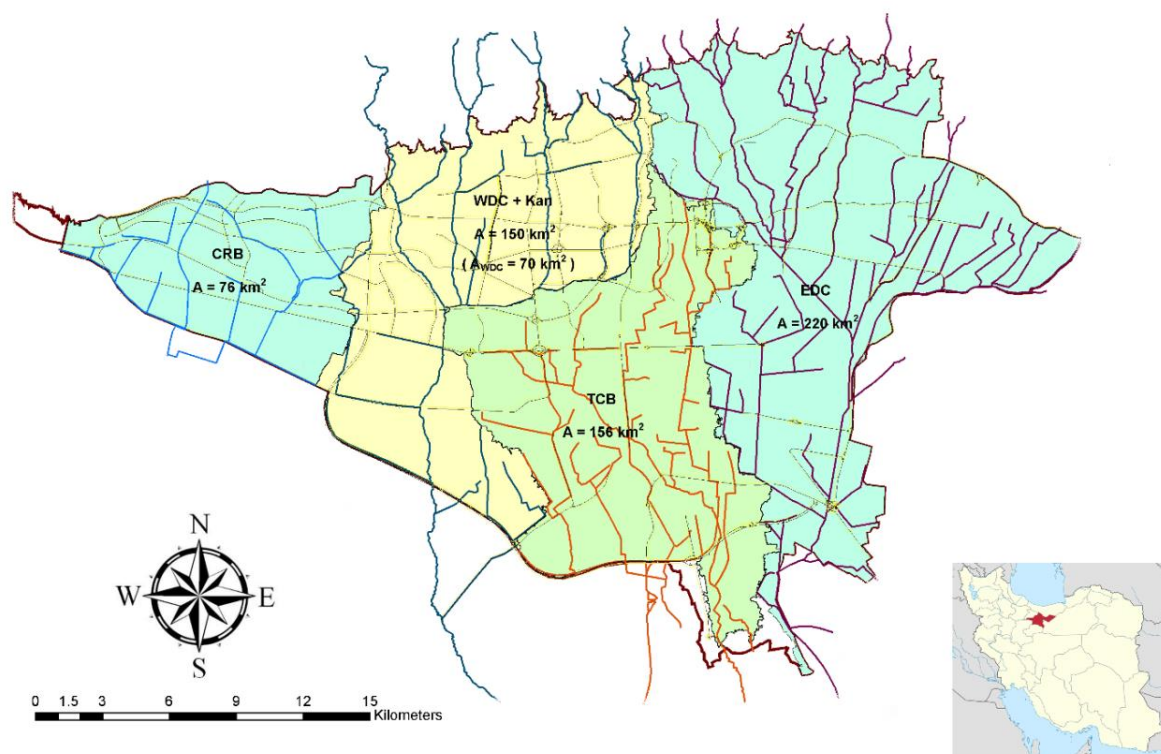


Figure 1. Geographical location and drainage system of Tehran city. Map showing the spatial distribution of urban river sampling stations across eastern, central, and western tributaries of Tehran's drainage zones.

2.2. In-situ Measurement, Preservation, and Transfer and Laboratory Measurements

In the initial phase of the study, sampling stations were strategically selected to represent the environmental conditions of Tehran as a densely populated metropolitan area characterized by multiple sources of contamination. Stations were chosen based on their accessibility and their spatial distribution across the urban river network to ensure comprehensive coverage of water quality conditions throughout

the city.

WQVs were categorized into two groups (Table 1). The first group included parameters that could be measured in situ, such as pH, temperature, and dissolved oxygen (DO). These were measured using a portable multi-parameter device (YSI ProDSS) following standard field procedures. The second group consisted of variables that required laboratory analysis, including various chemical constituents, which were measured using spectrophotometric methods in accordance with LSASDPROC-201-R6 protocols.

Table 1. Classification of analyzed water quality parameters based on chemical nature and toxicity.

Element	Metal	Heavy Metal	Toxic	Non-Metal
Potassium (K)	*			
Sodium (Na)	*			
Phosphate (PO ₄)	*			

Element	Metal	Heavy Metal	Toxic	Non-Metal
Ammonia (NH ₃)			*	
Fluorine (F)			*	
Chlorine (Cl)			*	
Detergent			*	
Chemical Oxygen Demand (COD)				* (unit)
Biochemical Oxygen Demand (BOD ₅)				* (unit)
Manganese (Mn)	*			
Iron (Fe)	*			
Zinc (Zn)	*			
Nickel (Ni)	*	*	*	
Lead (Pb)	*	*	*	
Copper (Cu)	*		*	
Chromium (Cr)	*	*	*	
Arsenic (As)	*		*	
Magnesium (Mg)	*			
Oil (OIL)			*	

To ensure the reliability and accuracy of data, quality assurance and quality control (QA/QC) procedures for surface water sampling were conducted in compliance with the U.S. Environmental Protection Agency (EPA) Region 4's Standard Operating Procedure (SOP) LSASDPROC-201-R6. These protocols ensured proper sample handling, preservation, and analysis throughout the sampling and measurement process.

2.3. Data Analysis

In this study, a new BI for urban rivers was introduced using linear regression between BOD₅ and COD. The accuracy and robustness of the proposed index were evaluated using statistical metrics such as the coefficient of determination (R²) and the p-value [30].

To further investigate the behavior of BI and its relationship with other water quality variables (WQVs), several analytical approaches were employed. Clustering analysis was used to identify groups of variables that showed similar patterns and to determine which variables tended to cluster with BOD₅ or COD. Spearman's rank correlation coefficient was applied to examine pairwise relationships among WQVs, while linear regression was used to assess the strength of correlations through R² values.

Additionally, advanced machine learning techniques such

as SHapley Additive exPlanations (SHAP) [31] and Random Forest Regression were utilized to validate and interpret the influence of different WQVs on BI. These methods provided deeper insights into the underlying relationships and helped confirm the reliability of the developed index.

Finally, a predictive equation was formulated to estimate BI values efficiently. This model offers a cost-effective and time-saving tool for early assessment of water quality, potentially serving as an early warning indicator in urban river monitoring and management programs.

3. Result and Discussion

Linear regression analysis between BOD₅ and COD revealed a strong and statistically significant relationship (Figure 2), with an R² value of 0.92 and a p-value less than 0.0001. Based on this relationship, the BI for the urban river was calculated as 0.6. This value is notable, as it suggests that the biodegradability of organic matter in urban rivers may differ significantly from that in natural or less-impacted water bodies, likely due to the higher levels of anthropogenic stressors in urban environments.

$$BI = \frac{BOD_5}{COD} = 0.62 \quad (1)$$

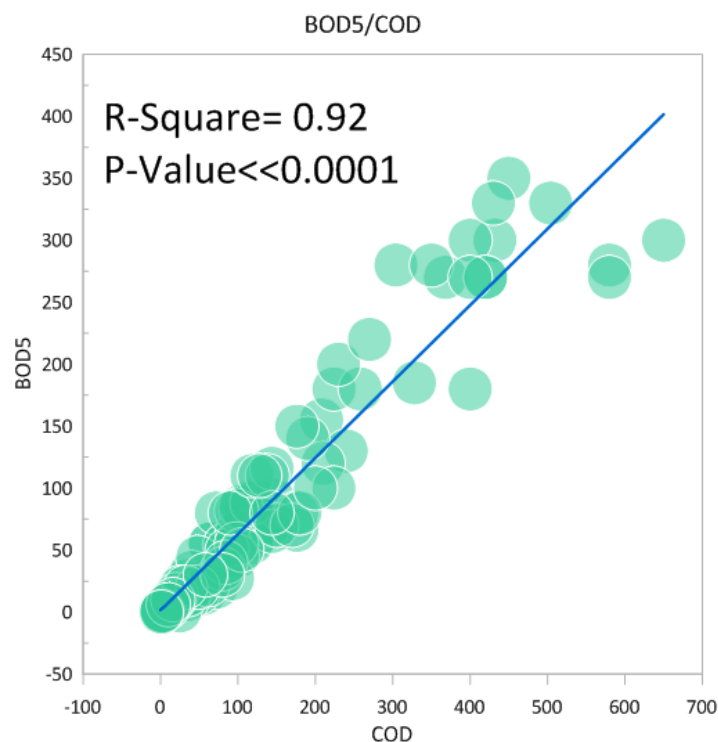


Figure 2. Scatter plot and linear regression between BOD_5 and COD. The strong correlation ($R^2 = 0.92$, $p < 0.0001$) illustrates the foundation for calculating the BI in the studied urban river system.

A BI value of 0.6 indicates a relatively high potential for organic substances to be decomposed by microorganisms such as bacteria and fungi into simpler, non-toxic end-products like water, carbon dioxide, and biomass. This

highlights the importance of developing specific BI indicators for urban rivers, which are often subject to more complex and variable pollutant loads compared to other types of surface waters.

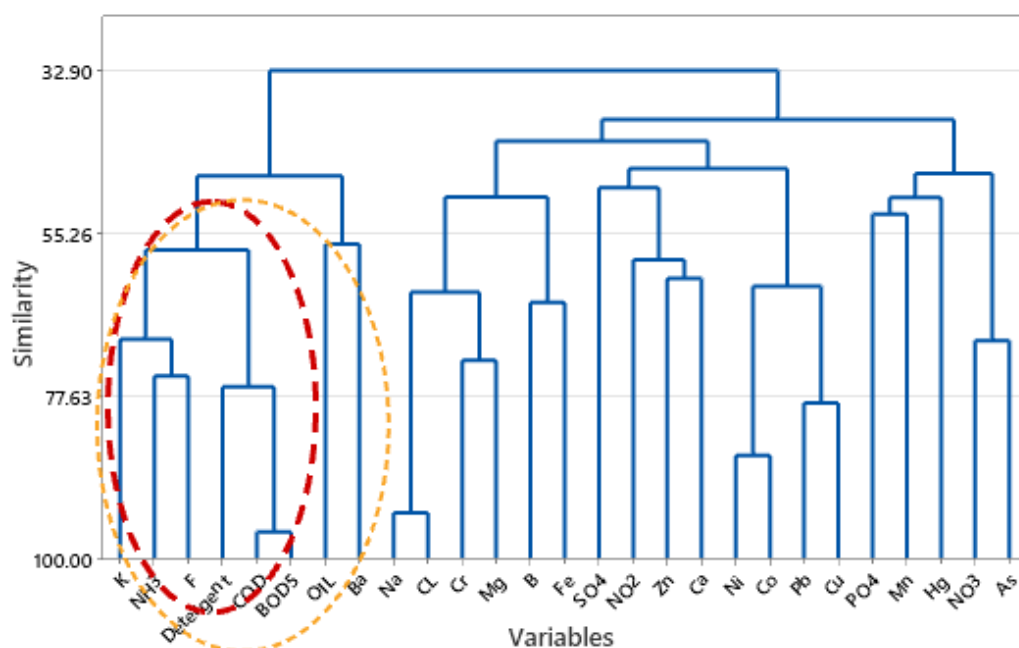


Figure 3. Clustering analysis of water quality variables. Dendrogram showing the grouping of BOD_5 , COD, and detergents with other key WQVs such as ammonia, fluoride, and potassium, indicating similar spatial patterns or pollution sources.

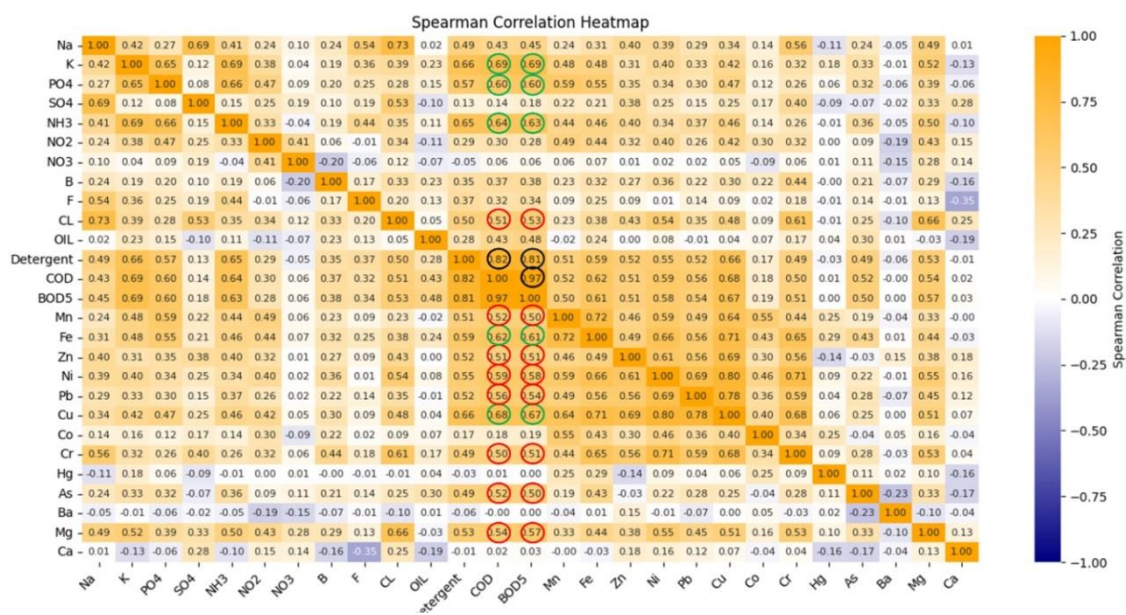


Figure 4. Spearman correlation heatmap of water quality variables. This figure displays significant correlations between BOD_5/COD and several chemical indicators, with detergents showing the highest correlation ($r = 0.82$).

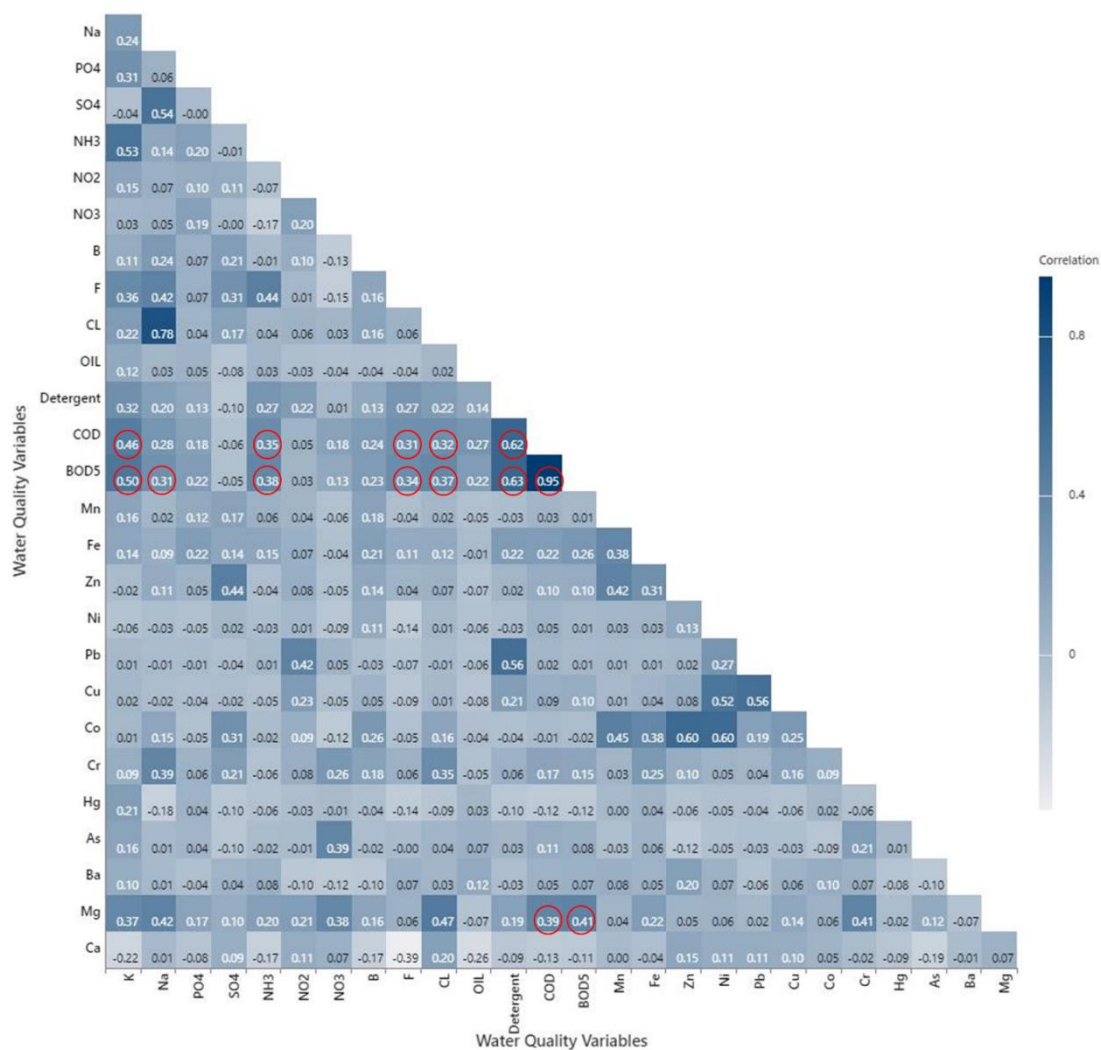


Figure 5. Linear regression between BI and detergent concentration. The plot shows a strong linear relationship ($R^2 = 0.63$) between BI (BOD_5/COD) and detergent concentration, confirming detergent as a reliable predictor of organic pollutant biodegradability in urban rivers.

Clustering analysis revealed that BOD₅ and COD were grouped with several water quality variables, including detergents, fluoride (F), potassium (K), and ammonia (NH₃), indicating similar distribution patterns and potential common sources of pollution (Figure 3). Additionally, a weaker association was observed with oil and barium (Ba), suggesting some level of co-occurrence or shared influence in specific conditions [31]. Among these, the strongest similarity was found between detergents and both BOD₅ and COD, highlighting detergents as a key contributor to the organic pollution and biodegradability dynamics within the urban river system.

Spearman's correlation analysis [32] demonstrated a significant positive relationship between BOD₅ and COD with several water quality variables, including potassium (K), phosphate (PO₄³⁻), sulfate (SO₄²⁻), ammonia (NH₃), iron (Fe), and copper (Cu), all exhibiting correlation coefficients greater than 0.60 (Figure 4).

The strongest correlation was observed between BOD₅/COD and detergent concentration, with a Spearman coefficient of 0.82 (Figure 5). This strong association was further supported by linear regression analysis, which yielded an R²-value of 0.63, confirming the influence of detergents on organic pollution levels in the urban river system.

Shapley Additive exPlanations (SHAP) (Figure 6c) and Random Forest Regression (Figure 6a and 6b) were employed as novel analytical approaches to validate the strong relationship between BOD₅, COD, and detergent concentrations. Both methods confirmed that detergent is a key predictor of organic pollution in urban rivers. Given that detergent levels are faster and more cost-effective to measure compared to BOD₅, a predictive equation for the BI was developed using detergent as a primary input. This predictive model demonstrated robust accuracy, achieving an R²-value of 0.7, indicating its potential as an efficient, low-cost tool for estimating BI in urban river monitoring programs.

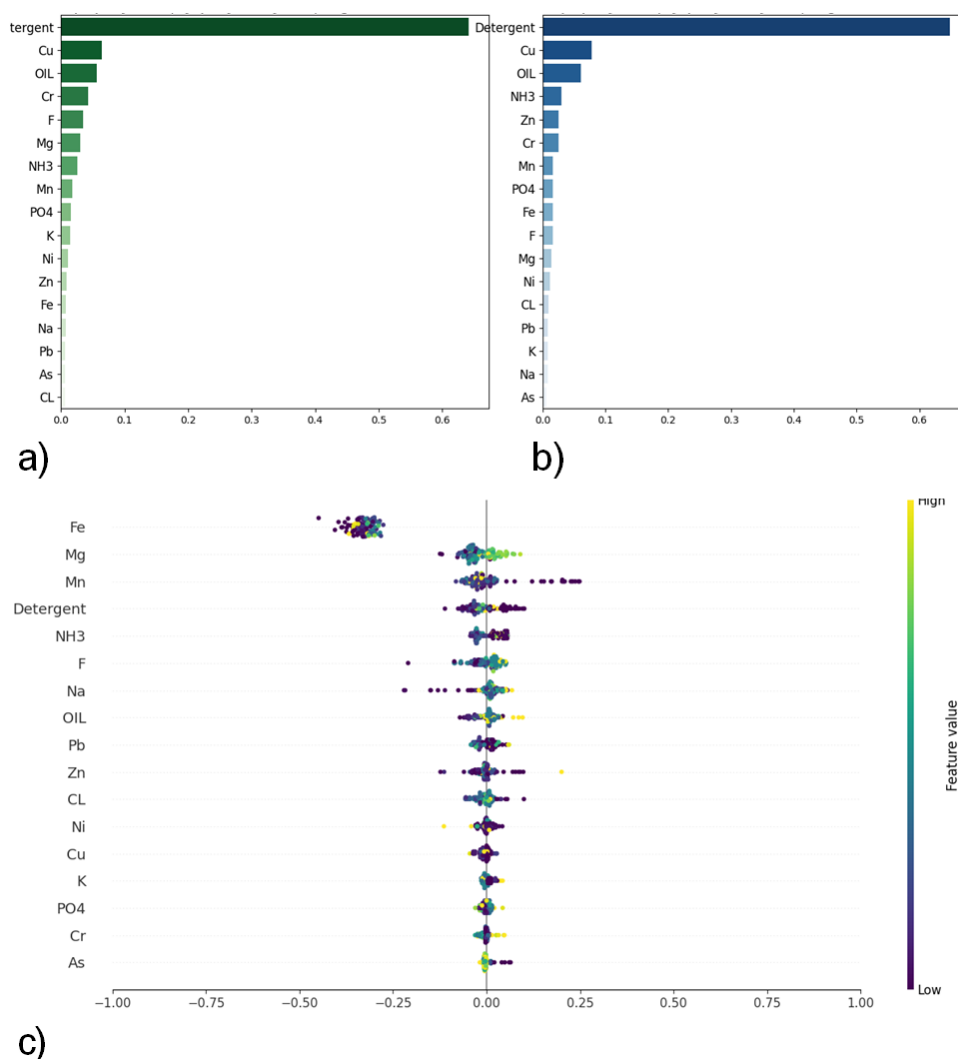


Figure 6. a) Random Forest regression model for predicting BOD₅ values based on water quality variables. b) Random Forest regression model for predicting COD values using the same input features. c) SHapley Additive exPlanations (SHAP) summary plot indicating the relative importance of variables in predicting the BI, with detergent concentration identified as the most influential feature.

All analyses consistently indicated that among the various water quality variables (WQVs), detergent was the only variable strongly correlated with the BI and suitable for its prediction. As a result, a linear regression model was developed using detergent concentration as the sole predictor of BI. The model demonstrated acceptable performance with a coefficient of determination (R^2) of 0.7, indicating a strong predictive capability. The proposed equation for estimating BI in urban rivers is as follows:

$$BI = 4.2 \times \text{Detergent} - 0.21 \quad (2)$$

This equation offers a practical and low-cost alternative for estimating BI, particularly valuable in urban water monitoring where traditional BI measurements (e.g., BOD₅ and COD) are more time-consuming and resource-intensive.

4. Conclusion

This study introduces a new BI specific to urban rivers and demonstrates that detergent concentration is a strong predictor of BI. A statistically significant correlation between BOD₅ and COD yielded a BI of 0.6 for Tehran's urban river system, indicating a high potential for organic pollutant degradation. Clustering and correlation analyses highlighted the influence of detergents on organic pollution dynamics, which was further validated by SHAP and Random Forest techniques. The resulting regression model, based solely on detergent concentration, offers a rapid and cost-effective method for predicting BI. This approach enables more efficient urban river monitoring and could be a valuable tool for policymakers and environmental managers focused on improving water quality in highly urbanized settings.

Abbreviations

BOD ₅	Biochemical Oxygen Demand (5-Day)
COD	Chemical Oxygen Demand
BI	Biodegradability Index
WQVs	Water Quality Variables
SHAP	SHapley Additive exPlanations
R^2	Coefficient of Determination
EPA	Environmental Protection Agency
DO	Dissolved Oxygen
ORCID	Open Researcher and Contributor ID
SOP	Standard Operating Procedure
BOD ₅ /TOC	Biochemical Oxygen Demand to Total Organic Carbon
COD/TOC	Chemical Oxygen Demand to Total Organic Carbon
BOD ₅ /TN	Biochemical Oxygen Demand to Total Nitrogen
BOD ₅ /TP	Biochemical Oxygen Demand to Total Phosphorus

BOD ₅ /COD	Biochemical Oxygen Demand to Chemical Oxygen Demand
K	Potassium
Na	Sodium
PO ₄	Phosphate
NH ₃	Ammonia
F	Fluorine
Cl	Chlorine
Mn	Manganese
Fe	Iron
Zn	Zinc
Ni	Nickel
Pb	Lead
Cu	Copper
Cr	Chromium
As	Arsenic
Mg	Magnesium
OIL	Oil

Author Contributions

Amin Arzhangi: Formal Analysis, Investigation, Methodology, Software, Validation, Visualization, Writing - original draft

Sadegh Partani: Conceptualization, Data curation, Project administration, Supervision, Writing - review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

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