



ORIGINAL ARTICLE

Quantitative Analysis of Phosphate in Laundry Detergents Using the Molybdenum Blue Method

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Abstract

Phosphates are commonly used in laundry detergents as water softening agents, but their excessive discharge into aquatic environments has been linked to eutrophication and the deterioration of water quality. Despite international efforts to regulate phosphate use, phosphate-based detergents remain prevalent in regions like Malaysia, where regulatory oversight is limited. This study aimed to quantify phosphate concentrations in selected commercial liquid laundry detergents available in the Malaysian market and evaluate their potential environmental impact using the molybdenum blue spectrophotometric method, which measures the blue-colored phosphomolybdate complex at 650 nm. Five detergent brands (A to E) were analyzed following a 1:500 dilution protocol. Phosphate levels were determined from a calibration curve constructed using standard solutions (0–5 mg/L as PO_4^{3-}). The method showed excellent linearity ($R^2 = 0.9885$) and good precision, with relative standard deviations (RSD) below 10% for both standard and sample measurements. The phosphate concentrations obtained for the detergent samples were 0.669 mg/L (A), 0.555 mg/L (B), 0.411 mg/L (C), 0.476 mg/L (D), and 1.390 mg/L (E), with Brand E showing the highest level and Brand C the lowest. When translated to estimated phosphate discharge per laundry cycle, values ranged from 20.6 mg to 69.5 mg per 50-liter wash, all below the European Union's threshold of 500 mg per standard dose, indicating general compliance among tested samples. However, repeated domestic use of detergents with higher phosphate levels may still contribute cumulatively to phosphate loading in wastewater systems, highlighting potential long-term ecological concerns.

Keywords: phosphate pollution; laundry detergent; water quality; environmental impact; spectrophotometry; molybdenum blue.

Introduction

Understanding phosphate contamination from household detergents is critical to evaluating nutrient pollution in domestic wastewater systems. This study addresses three central research

questions: (i) What are the phosphate concentrations in commercially available liquid laundry detergents in the Malaysian market? (ii) How do these concentrations compare with international regulatory thresholds such as those established by the European Union? and (iii) What are the potential environmental implications of phosphate discharge from household detergent use under local wastewater conditions?

Phosphorus is an essential nutrient that supports the growth and metabolic functions of plants and animals, contributing significantly to overall ecosystem productivity (Wang et al., 2023). However, excessive amounts of phosphorus, particularly in the form of orthophosphate, can lead to serious environmental problems when released into aquatic environments (Duhamel, 2025). One of the major sources of phosphorus pollution is the widespread use of phosphate-based compounds in household detergents. These compounds, commonly including sodium tripolyphosphate (STPP), are added to formulations to soften hard water and enhance cleaning efficiency (Agbazue et al., 2015). During washing and wastewater discharge, STPP and related polyphosphates may hydrolyze into orthophosphate, which is the reactive form contributing directly to eutrophication, a condition caused by elevated nutrient levels that promote the excessive growth of algae and aquatic plants (Jin et al., 2024).

The environmental impacts of eutrophication are well documented. Excessive algal growth disrupts aquatic ecosystems by reducing light penetration, depleting dissolved oxygen during decomposition, and creating hypoxic or "dead zones" where aquatic life cannot survive (OSPAR, 2023). These conditions degrade water quality, harm biodiversity, interfere with recreational activities, and may introduce toxins that pose risks to human and animal health. Phosphate pollution is therefore considered a critical threat to freshwater environments, particularly in regions with limited or inefficient wastewater treatment infrastructure (Duhamel, 2025).

In response to these environmental concerns, many countries have introduced regulations to limit the use of phosphates in household cleaning products. For example, the European Union and Canada have adopted strict phosphate restrictions, leading to the widespread adoption of phosphate-free or phosphate-reduced detergents (Environment and climate change Canada, 2020; European commission, 2012). While these policies have successfully reduced phosphate emissions in developed regions, phosphate-based detergents remain prevalent in developing countries, including those in Southeast Asia. In Malaysia, such products are still widely used, underscoring the importance of locally focused studies to evaluate their phosphate content and potential environmental effects (Low et al., 2021).

Despite global progress in limiting phosphate use, Malaysia currently lacks specific regulations governing phosphate content in household detergents (Chong et al., 2019). Wastewater treatment facilities across the country are not uniformly equipped to remove dissolved phosphates effectively, allowing these compounds to enter rivers and reservoirs that serve domestic and agricultural needs (Hanafiah et al., 2021; Jega et al., 2025). Moreover, detergent formulations in Southeast Asia often differ from those in Western markets due to the use of regionally sourced raw materials and varying manufacturing standards (UNEP COBSEA, 2021). These factors make local phosphate quantification essential for understanding actual environmental discharge levels and for supporting evidence-based policymaking. Therefore, generating region-specific data on phosphate concentrations in Malaysian detergents provides a necessary foundation for future regulation, wastewater management, and the promotion of eco-friendly formulations.

Regional studies have shown that nutrient pollution remains a transboundary concern in the East Asian Seas region (UNEP COBSEA, 2021), emphasizing the need for consistent data to guide management interventions. Research from China and neighbouring countries further indicates that detergent-derived phosphates are a significant but controllable source of phosphorus in wastewater systems, and that reformulating products can substantially reduce aquatic pollution (Chen et al., 2022; van Puijenbroek et al., 2018). These findings highlight the

importance of localized monitoring, especially in developing regions where treatment capacity and product formulations vary widely.

Several analytical techniques have been developed for phosphate quantification, including ion chromatography, inductively coupled plasma spectrometry, and flow injection analysis. Although these methods offer high sensitivity and selectivity, they are often expensive and require complex operation under controlled laboratory conditions. In recent years, alternative approaches such as electrochemical sensors and spectrofluorometric assays have also been explored for trace phosphate detection in environmental samples (Ruiz-Calero & Galceran, 2005; Motomizu & Li, 2005; Karadağ et al., 2018; Zhu & Ma, 2020). Nevertheless, for routine analysis where accessibility, simplicity, and cost-effectiveness are essential, the molybdenum blue spectrophotometric method remains the preferred choice (Zhai, 2023). In this colorimetric technique, orthophosphate reacts with ammonium molybdate under acidic conditions to form a phosphomolybdate complex, which is subsequently reduced, typically using stannous chloride or hydrazine hydrate, to produce a blue-colored compound. The intensity of this color, measured at 650 nm, is directly proportional to the phosphate concentration. This well-established method is widely applied for both natural water and detergent samples, providing reliable quantification even at low concentrations (Ismail, 2023).

This study applies the molybdenum blue method to determine phosphate concentrations in selected commercial liquid laundry detergents available in the Malaysian market. The objective is to assess whether these products meet international standards for phosphate discharge and to evaluate their potential environmental impact. Although detergent compositions have been studied in various regions (Chong et al., 2019), limited data exist on phosphate levels in Malaysian detergents or other Southeast Asian markets (Agbazue et al., 2015; Thapa & Khadka, 2023). By establishing baseline phosphate data for Malaysian detergents, this study aims to provide actionable evidence to support future national policy development, promote sustainable detergent reformulation, and reduce phosphate-related water pollution in the region.

Materials and Methods

Chemicals

All chemicals, including ammonium molybdate tetrahydrate ((NH₄)₆Mo₇O₂₄·4H₂O), stannous chloride dihydrate (SnCl₂·2H₂O), potassium dihydrogen phosphate (KH₂PO₄), sulfuric acid (H₂SO₄), and glycerine, were sourced from Sigma-Aldrich (Missouri, USA). Solutions were prepared as follows: ammonium molybdate reagent (2.5% w/v (NH₄)₆Mo₇O₂₄·4H₂O in 5 M aqueous H₂SO₄), stannous chloride solution (2.5% w/v SnCl₂·2H₂O in glycerine), and phosphate stock solution (20 mg/L as PO₄³⁻ from KH₂PO₄ in aqueous solution). All aqueous solutions were prepared using sterilized deionized water (deH₂O) produced by a Sartorius Arium[®] Pro ultrapure water system (Göttingen, Germany).

Instruments

A PerkinElmer Lambda 25 UV-Visible spectrophotometer (Massachusetts, USA), equipped with 1 cm path-length quartz cuvettes, was used for absorbance measurements.

Research Design

This study employed a quantitative, laboratory-based experimental design to quantify phosphate content in commercial liquid laundry detergents. The molybdenum blue method, a colorimetric technique, was selected for its high sensitivity and specificity in detecting phosphate in aqueous

solutions. The method is based on the formation of a blue-colored molybdophosphate complex, with absorbance measured at 650 nm using UV-Visible spectrophotometry.

Sample Selection

Five liquid laundry detergent brands (labelled A to E) were selected from the Malaysian market based on their widespread availability and representation across major household detergent categories to ensure market relevance and comparability. The selection included formulations with distinct cleaning claims: a concentrated stain-removal detergent (A), a color-care detergent (B), an economy general-purpose detergent (C), an antibacterial detergent (D), and a premium formulation with enhanced cleaning performance (E). Only liquid formulations were analyzed to maintain uniformity in sample preparation and testing procedures.

To maintain ethical neutrality and avoid any perception of commercial bias or endorsement, the identities of the detergent brands are anonymized in this study. This approach is consistent with standard academic practice, especially when brand identity is not essential to the research objectives.

Preparation of Standard Phosphate Solutions

Standard phosphate solutions were prepared by serial dilution of the phosphate stock solution using deH_2O . Six working standards with concentrations of 0, 1, 2, 3, 4, and 5 mg/L as PO_4^{3-} were prepared to generate a calibration curve.

Preparation of Detergent Samples

Each detergent sample was diluted at a ratio of 1:500 (1 mL detergent to 500 mL tap water) to simulate typical laundry usage and to ensure that phosphate concentrations remained within the measurable range of the molybdenum blue method. Diluted samples were thoroughly mixed to ensure homogeneity before analysis.

Color Development Procedure

For both standard and detergent samples, 25 mL of solution was transferred into a clean container. To each sample, 1.0 mL of ammonium molybdate reagent and two drops of stannous chloride solution were added sequentially. The mixtures were gently stirred and allowed to stand for exactly 10 minutes to ensure consistent and complete color development of the molybdophosphate complex. The 0 mg/L standard solution was used as a blank to correct for potential reagent-related absorbance.

This procedure specifically quantifies orthophosphate directly present in the detergent samples. No digestion or hydrolysis step was performed to convert condensed phosphate species, such as STPP, into orthophosphate; therefore, the reported values represent orthophosphate concentrations only.

Absorbance Measurement and Calibration Curve Construction

Absorbance readings were taken at 650 nm using the UV-Visible spectrophotometer. Each measurement was performed in triplicate, and mean absorbance values were recorded. Standard deviations of the triplicate measurements were calculated to assess precision. A linear calibration curve was constructed by plotting mean absorbance values against their corresponding phosphate concentrations using Microsoft Excel. The coefficient of determination (R^2) was evaluated to confirm linearity, with R^2 values ≥ 0.98 accepted as valid.

Phosphate Determination in Detergent Samples

Phosphate concentrations in detergent samples were calculated by referencing their absorbance values to the calibration curve. Final results were expressed in mg/L, based on the linear relationship established from the standard phosphate solutions.

A simplified flowchart summarizing the analytical procedure for phosphate quantification using the molybdenum blue spectrophotometric method is shown in Fig. 1.

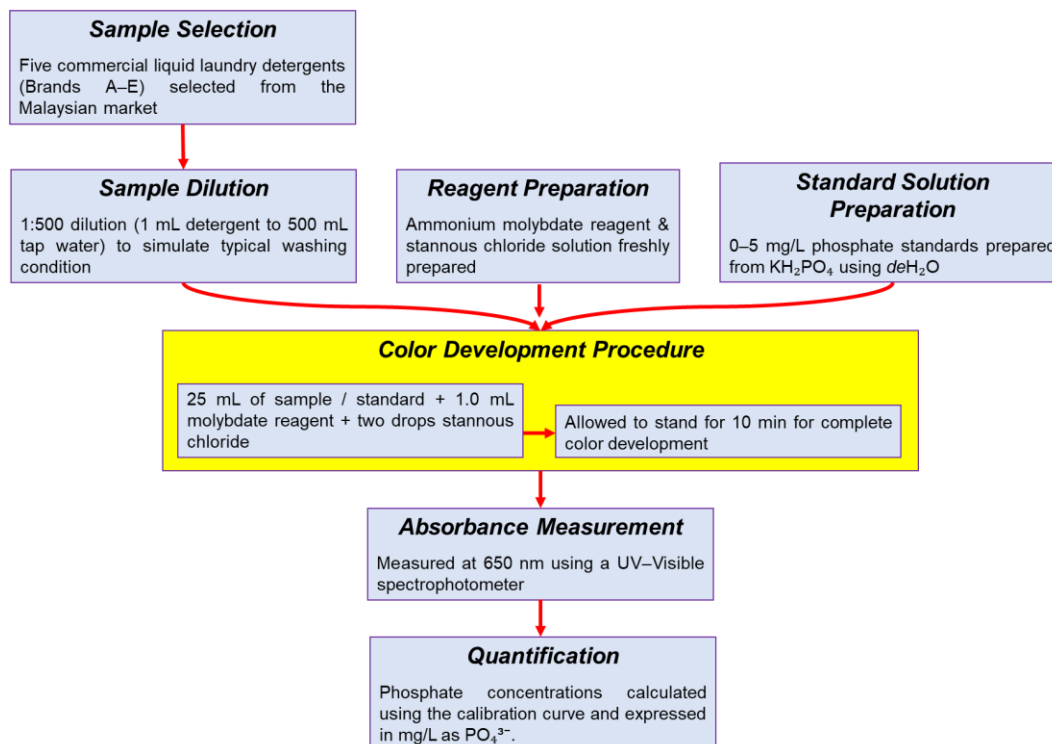


Figure 1. Flowchart of the analytical steps for phosphate determination in detergent samples using the molybdenum blue spectrophotometric method.

Results and Discussion

Phosphate Calibration Curve and Analytical Performance

The calibration curve for phosphate quantification was generated using standard solutions ranging from 0 to 5 mg/L of phosphate (as PO_4^{3-}), analyzed via the molybdenum blue method at 650 nm. As shown in Fig. 2, the calibration curve demonstrated a strong linear relationship between absorbance and phosphate concentration, with a coefficient of determination (R^2) of 0.9885. This confirms the reliability of the method for quantitative phosphate determination within the tested range.

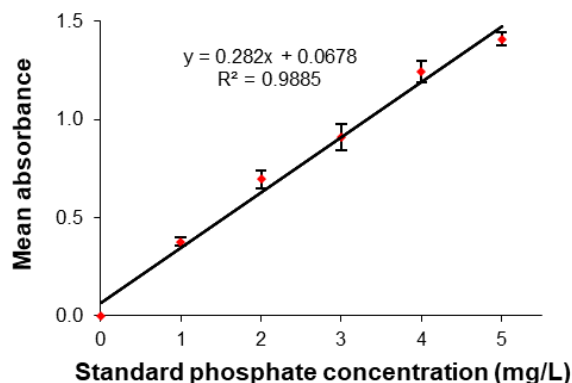


Figure 2. Linear calibration curve of mean absorbance for phosphate quantification using the molybdenum blue method. The error bars indicate the standard deviation from triplicate experiments ($n = 3$).

The relative standard deviation (RSD) for triplicate absorbance readings across the standards ranged from 2.23% to 7.33%, all below the 10% threshold, indicating excellent precision and consistency. These results affirm the analytical suitability of the molybdenum blue method for detecting phosphate in aqueous detergent matrices.

Phosphate Quantification in Laundry Detergent Samples

The phosphate content of five commercial liquid laundry detergents was determined using the same colorimetric approach. Absorbance measurements for each sample were conducted in triplicate, and the results are presented in Fig. 3. The RSD for these measurements ranged from 3.57% to 8.80%, indicating good reproducibility. Variations in absorbance values among the brands reflect differences in formulation composition and phosphate loading.

Using the calibration curve from Fig. 2, phosphate concentrations were calculated from the average absorbance readings. As summarized in Table 1, phosphate concentrations in the detergent samples ranged from 0.411 mg/L to 1.390 mg/L, with Brand C showing the lowest level and Brand E as a notable outlier with the highest concentration. Brand E's elevated phosphate content may reflect formulation differences and suggests a comparatively higher potential for phosphate discharge during repeated domestic washing. Brands A, B, and D exhibited intermediate concentrations, indicating moderate environmental impact under typical usage conditions.

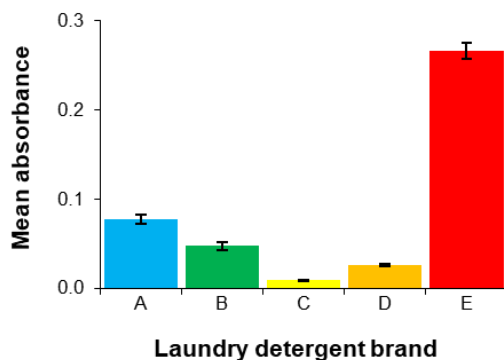


Figure 3. Mean absorbance for laundry detergent phosphate quantification using the molybdenum blue method. The error bars indicate the standard deviation from triplicate experiments ($n = 3$).

Table 1. Calculated phosphate concentrations in laundry detergent samples using the molybdenum blue method.

Laundry Detergent Brand	Calculated Phosphate Concentration (mg/L)
A	0.669
B	0.555
C	0.411
D	0.476
E	1.390

Note: Phosphate concentrations (mg/L as PO_4^{3-}) are for 1:500 diluted laundry detergent samples. They were calculated using the calibration curve (Fig. 2) from standard solutions (0–5 mg/L) and average absorbance from three measurements at 650 nm (Fig. 3).

The measured phosphate concentrations reflect realistic usage conditions due to the controlled sample preparation approach. To achieve this, each detergent sample was diluted at a ratio of 1:500 prior to analysis, simulating common household washing practices. This dilution factor corresponds to the average detergent-to-water ratio commonly applied in standard washing machine cycles, as recommended by major detergent manufacturers and supported by previous phosphate quantification studies (Agbazue et al., 2015; Thapa & Khadka, 2023). Such dilution was necessary not only to represent actual domestic washing conditions but also to ensure that phosphate concentrations remained within the linear detection range of the molybdenum blue method, thereby maintaining both analytical accuracy and environmental relevance to domestic wastewater discharge.

Tap water was used for sample dilution to better simulate real household washing scenarios, as detergents are designed to perform in natural water matrices rather than deionized media. The presence of common ions such as calcium (Ca^{2+}), magnesium (Mg^{2+}), and chloride (Cl^-) in tap water reflects realistic washing conditions, where phosphate compounds function as chelating agents to sequester hardness ions and enhance cleaning efficiency (Martínez-Huitle & Panizza, 2018; Thapa & Khadka, 2023). In contrast, deH_2O was used to prepare the standard phosphate solutions to ensure calibration accuracy and eliminate potential background interference. Although differences in ionic composition between standards and detergent samples could theoretically cause minor matrix interactions, these effects were minimized by the relatively low ionic strength and the strong stability of phosphate–molybdate complexes under acidic conditions. The calibration curve constructed from the standards exhibited excellent linearity ($R^2 = 0.9885$), and the overall analytical precision was satisfactory ($\text{RSD} < 10\%$) for both standards and detergent samples, confirming the reliability of the method (Habibah et al., 2018; Ismail, 2023).

It should be noted that the molybdenum blue method quantifies only orthophosphate, the readily reactive form of phosphorus. Condensed phosphates such as STPP, if present, are not fully converted to orthophosphate under the conditions used in this study, as no digestion step was applied before color development (Habibah et al., 2018). Consequently, the reported values represent the bioavailable phosphate fraction in the detergent formulations rather than the total phosphate content. This provides a conservative estimate that emphasizes the portion of phosphorus most relevant to immediate environmental impact and eutrophication potential.

Furthermore, phosphate levels in laundry detergents can be influenced by other formulation components, such as surfactants, fillers, and chelating agents, which may interact with phosphate or affect its solubility. The observed differences between brands likely reflect both phosphate content and formulation variations (Agbazue et al., 2015; Bajpai et al., 2007; Yunusov & Zaytseva, 2023). Such factors should be considered when interpreting potential environmental discharge,

as repeated domestic use of phosphate-containing detergents can contribute cumulatively to phosphate loading in wastewater. This underscores the importance of continuous monitoring and guidance to mitigate impacts on water quality.

Estimated Phosphate Discharge Per Laundry Cycle

To better assess the environmental implications of the measured concentrations, the phosphate discharge per single laundry cycle was estimated based on a commonly used household washing machine volume of 50 liters. The calculation assumes a typical liquid detergent dose of 1 mL per liter of wash water (50 mL per 50 L wash), which is consistent with manufacturer recommendations for concentrated liquid detergents. By multiplying each sample's phosphate concentration by 50 L, the amount of phosphate released per wash was approximated.

The estimated phosphate discharge values for all detergent brands are summarized in Table 2. Brand E exhibited the highest discharge at 69.5 mg per wash, identifying it as an outlier. Brand A released approximately 33.5 mg, followed by Brand B at 27.8 mg, Brand D at 23.8 mg, and Brand C at 20.6 mg per wash cycle. These values remain well below the European Union's regulatory limit of 500 mg phosphate per standard dose of detergent, which refers to the recommended usage amount for a single wash (European commission, 2012). Nonetheless, while individually compliant, repeated use of phosphate-containing detergents, particularly those with higher levels like Brand E, can contribute significantly to cumulative phosphate pollution.

Environmental implications

Phosphate is a critical nutrient that, when present in excess, accelerates eutrophication in freshwater ecosystems. This process promotes the overgrowth of algae and aquatic plants, leading to oxygen depletion, habitat degradation, and in severe cases, the formation of hypoxic "dead zones." In addition, harmful algal blooms may produce toxins that pose risks to both aquatic organisms and human health.

Although all tested detergent brands remain below the EU's 500 mg phosphate per dose threshold (European commission, 2012), the estimated discharge values suggest that certain products, particularly Brand E, could still pose environmental risks through repeated domestic use. Brands A and B, with moderate concentrations, may also contribute to this burden over time, while Brands C and D appear to have comparatively lower impact.

In Southeast Asia, phosphate pollution from household detergents remains a pressing concern due to varying levels of regulatory enforcement and limited wastewater treatment capacity (UNEP COBSEA, 2021; van Puijenbroek et al., 2018; Bhagat et al., 2024). Region-specific studies indicate that household detergents are a significant source of phosphorus loading in local aquatic environments, emphasizing the need for targeted policy measures, improved wastewater management, and public awareness campaigns.

Many regulatory agencies have imposed limits on phosphate levels in detergents to address these environmental concerns. The EU and several U.S. states have implemented strict standards to phase out or limit phosphate in household cleaning products. The findings of this study reinforce the value of such regulations and highlight the ongoing need for formulation reform, particularly for brands with elevated phosphate levels. In the Southeast Asian context, these results support the development of region-specific guidelines and encourage manufacturers to consider phosphate-reduced formulations to mitigate eutrophication risks.

Table 2. Estimated phosphate discharge per 50 L laundry wash

Laundry Detergent Brand	Estimated Phosphate Discharge per 50 L Wash (mg)	Comparison with EU Limit (500 mg per dose)
A	33.5	Below
B	27.8	Below
C	20.6	Below
D	23.8	Below
E	69.5	Below

Note: Estimated discharge values were calculated using the measured phosphate concentrations and a household washing machine volume of 50 L. The EU limit refers to the recommended detergent dose per wash (European commission, 2012).

Conclusion

This study demonstrated the effective application of the molybdenum blue method for quantifying phosphate concentrations in commercial liquid laundry detergents. The calibration curve showed excellent linearity and reproducibility, and the detergent samples exhibited a range of phosphate concentrations reflective of differences in product formulations. When translated to estimated discharge per household wash cycle, all brands were within international regulatory limits, though the cumulative environmental effects of repeated use remain a concern.

These findings highlight the importance of increased public awareness, stronger regulatory measures, and continuous reformulation of detergent products to minimize phosphate pollution in aquatic ecosystems. In line with this, manufacturers are encouraged to develop phosphate-free or low-phosphate formulations that comply with global environmental standards, such as detergents based on enzyme or plant-based cleaning agents and recent innovations in biodegradable surfactants (e.g., Zeolite- or citrate-based formulations) (Nagtode, 2023; Romero Vega, 2025; Yusriadi et al., 2020).

Given that Brand E was identified as a notable outlier, local authorities are encouraged to establish benchmark phosphate limits for liquid laundry detergents to mitigate environmental impact. Strengthening policy enforcement and advancing research on detergent composition and wastewater outcomes will further support sustainable household practices and long-term protection of aquatic environments.

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