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Temporal Variation of Ambient $PM_{2.5}$ and PM_{10} and Associated Non-Carcinogenic Health Risks in Thai Nguyen City, Vietnam

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KEYWORDS

$PM_{2.5}$
Seasonal variation
Non-carcinogenic health risk
Hazard quotient (HQ)
Thai Nguyen

ABSTRACT

This study examined the monthly and seasonal variations of ambient $PM_{2.5}$ and PM_{10} concentrations in Thai Nguyen City and quantitatively assessed the associated non-carcinogenic health risks for different population groups in 2021. The results reveal a pronounced seasonal pattern in air quality, with elevated fine particulate matter $PM_{2.5}$ concentrations during the dry and cold season. Monthly average $PM_{2.5}$ levels exceeded the national regulatory limit (QCVN 05:2023/BTNMT) in most months, with severe pollution episodes observed in January and December, when concentrations were more than 2.6 to over three times higher than the permissible standard. These findings indicate that $PM_{2.5}$ pollution in Thai Nguyen City is persistent and seasonally intensified, driven by unfavorable meteorological conditions combined with continuous emission sources such as traffic, industrial activities, and biomass burning. In contrast, PM_{10} concentrations remained below regulatory limits throughout the year, suggesting that fine particulate matter is the primary air pollutant of concern. Health risk assessment results show that, under normal conditions, exposure to particulate matter poses negligible health risks for infants, children, and adults. However, under worst-case scenarios, $PM_{2.5}$ exposure leads to unacceptable health risks for infants and children, with Hazard Quotient values exceeding the safety threshold, while adults remain below this threshold. Overall, $PM_{2.5}$ contributes substantially more to health risks than PM_{10} due to its higher toxicity and deeper penetration into the respiratory system.

1. Introduction

Ambient air pollution, particularly particulate matter (PM), has become one of the most serious environmental challenges affecting public health worldwide. Fine particulate matter ($PM_{2.5}$) and inhalable particulate matter (PM_{10}) are widely recognized as major air pollutants due to their adverse impacts on the respiratory and cardiovascular systems. $PM_{2.5}$, in particular, can penetrate deep into the alveolar regions of the lungs and enter the bloodstream, leading to increased risks of morbidity and premature mortality. Consequently, the assessment of particulate matter pollution and its health impacts has received growing attention in environmental and public health research. Particulate matter pollution is widespread in many urban areas of Vietnam, reflecting the increasing pressure from emission sources such as transportation, industrial activities, and rapid urbanization on air quality. In Hanoi, the average $PM_{2.5}$ concentration reached 35.5 – 59.4 μg/m^3, while PM_{10} levels reached 46.2 – 100.8 (Trần et al. 2023). In Viet Tri, $PM_{2.5}$ concentrations ranged from 33.8 to 51.7 μg/m^3 and PM_{10} from 48.7 to 70.3 μg/m^3 during the 2021–2023 period (Trần et al. 2023). Similarly, urban areas such as Ha Long and Da Nang recorded $PM_{2.5}$ concentrations ranging from 30.2–38.8 μg/m^3 and 15.7–21.8 μg/m^3, respectively, with corresponding PM_{10} concentrations varying between 43.9 to 67.7 μg/m^3 in Ha Long, and between 22 to 28.8 μg/m^3 in Da Nang (Anh et al. 2019).

In rapidly urbanizing cities of developing countries, air quality degradation is often exacerbated by increasing traffic density, industrial activities, and residential emissions, combined with unfavorable meteorological conditions. In Vietnam, several studies have reported elevated levels of particulate matter in major metropolitan areas (Hien et al. 2004; Nguyen et al. 2021, 2023; Bui et al. 2022; Makkonen et al. 2023; Tran et al. 2023); however, medium-sized industrial cities such as Thai Nguyen have received comparatively less attention, despite experiencing rapid urban expansion and increasing emission pressures. Located in the northeastern region of Vietnam, Thai Nguyen City is characterized by strong seasonal contrasts, which can significantly influence the dispersion and accumulation of airborne pollutants. Air pollution in Thai Nguyen province is influenced by multiple emission sources, including limestone quarrying and cement production activities in Dong Hy and Vo Nhai districts, waste treatment operations at the Da Mai landfill area, and emissions from nearby residential activities (Hoang and Bui 2022; Đăng et al. 2024). In addition, the rapid development of industrial and manufacturing facilities in the province contributes to the release of particulate matter and gaseous pollutants

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into the atmosphere (Hoang and Bui 2022). These emission sources are considered major contributors affecting the regional air quality.

Moreover, while previous studies have primarily focused on pollution levels and regulatory compliance, quantitative assessments of health risks associated with particulate matter exposure across different age groups remain limited, particularly in the context of episodic high-pollution events. Understanding age-specific vulnerability is essential for effective air quality management and the development of targeted public health protection strategies.

Therefore, the objective of this study is to analyze the temporal and monthly variations of $PM_{2.5}$ and PM_{10} concentrations in Thai Nguyen City and to quantitatively assess the potential non-carcinogenic health risks associated with particulate matter exposure for different population groups using the Hazard Quotient (HQ) approach.

1.1. Study area

Thai Nguyen City is classified as a Class I urban area and functions as the political, economic, and cultural hub of Thai Nguyen Province in the Northeastern region of Vietnam. The city is strategically located near the northern gateway of Hanoi Capital, providing favorable conditions for regional connectivity, commercial activities, and the development of industrial and service sectors in the northern midland and mountainous areas. Covering a total area of 222.12 km^2, Thai Nguyen City had a population of 358,986 inhabitants in 2022, resulting in a population density of 1,616 inhabitants per km^2 (Province 2023). The climate of Thai Nguyen City is characterized by a tropical monsoon regime, with two distinct seasons throughout the year: a hot and rainy season from May to October and a cool and dry season from November to April (Ha et al. 2020).

Previous air pollution mapping studies utilizing data from multiple monitoring stations have indicated that ambient air quality across the city generally ranges from moderate to poor, with higher pollution levels frequently observed in the central urban zones and along major transportation corridors (Đăng et al. 2024). These findings highlight a substantial degree of air pollution exposure among urban residential populations.

1.2. Data collection

Ambient particulate matter ($PM_{2.5}$ and PM_{10}) concentration data at the monitoring site on Hung Vuong road, Thai Nguyen City in 2021 were obtained from the World Air Quality Index (AQICN) platform (*https://aqicn.org*), which aggregates real-time and historical air quality measurements from local monitoring networks. The AQICN platform provides continuous monitoring data expressed in the Air Quality Index (AQI) format for key pollutants, including fine particulate matter ($PM_{2.5}$) and respirable particulate matter (PM_{10}), based on measurements collected by the Vietnam Center for Environmental Monitoring Portal (Cổng thông tin quan trắc môi trường) and other contributing data sources. The year 2021 was selected for analysis because it provides the most complete and continuous dataset, with available measurements covering all months of the year, thereby ensuring the reliability of temporal and seasonal variability assessments.

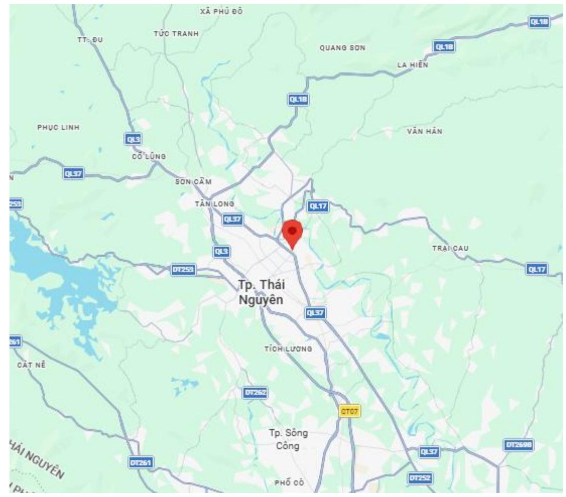

Figure 1. Monitoring site at Hung Vuong Road, Thai Nguyen City.

The selection of the ambient air quality monitoring site located along Hung Vuong Street, Thai Nguyen City, is considered representative of typical urban air pollution conditions in the city. Hung Vuong Street is one of the major traffic corridors, characterized by high traffic density and intensive commercial, service, and residential activities, and is therefore significantly influenced by emissions from vehicular traffic and urban activities. Concentrations of fine particulate matter ($PM_{2.5}$) and inhalable particulate matter (PM_{10}) measured at this location reasonably reflect the levels of particulate air pollution to which urban residents are routinely exposed. Consequently, data collected from this monitoring site provide a robust basis for assessing the status of ambient particulate matter pollution and for evaluating the potential health impacts associated with particulate matter exposure in Thai Nguyen City.

1.3. Multivariate Imputation by Chained Equations (MICE) Combined with Random Forest for Missing Data Imputation

The Multivariate Imputation by Chained Equations (MICE) method was employed to address missing values in the environmental monitoring dataset (Alahamade et al. 2021; Alsaber and Pan 2021; Hua et al. 2024). MICE is a multivariate imputation technique that estimates missing values based on the statistical relationships among multiple variables within the same dataset. This approach mitigates bias that may arise from case-wise deletion or the application of simplistic imputation methods.

Random Forest is a machine learning algorithm belonging to the ensemble learning family, constructed by aggregating multiple independent decision trees to enhance predictive performance (Alsaber and Pan 2021; Arriagada et al. 2021; Zhou et al. 2023). Each decision tree in the Random Forest is trained on a bootstrap sample of the original dataset, while at each split node, only a random subset of input variables is considered. This mechanism improves model robustness and reduces overfitting.

In this study, MICE was applied as a general imputation framework, with Random Forest selected as the regression model at each iteration step (Figure 2). This integrated approach leverages the iterative structure and statistical consistency of MICE, together with the strong predictive capability and flexibility of Random Forest (Shah et al. 2014; Doove et al. 2014).

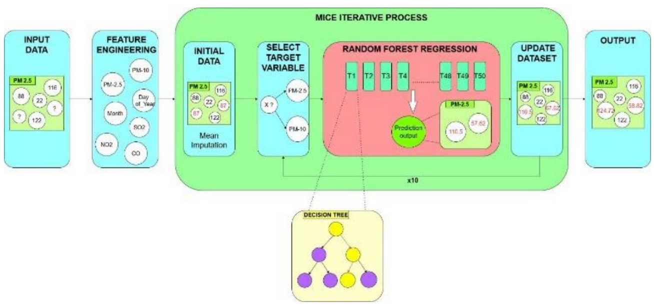

Figure 2. Workflow for Handling Missing Data Using the MICE–Random Forest Approach.

The input dataset comprised environmental monitoring variables, including time (Date), particulate matter concentrations ($PM_{2.5}$ and PM_{10}), and gaseous pollutants (NO_2, SO_2, and CO). Among these variables, $PM_{2.5}$ and PM_{10} contained missing values and were therefore selected as the target variables for imputation. To incorporate temporal variability, the Date variable was transformed into numerical features, namely Month and Day_of_Year. This transformation enables the Random Forest model to capture seasonal and cyclic patterns in pollutant concentration dynamics.

1.4. Health Risk Assessment

Exposure assessment aims to identify the population at risk, as well as the magnitude and duration of exposure to environmental hazards. In this study, inhalation was assumed to be the primary route of exposure to the monitored pollutants. Chronic exposure was evaluated under both normal and worst-case scenarios. In this study, human health risk assessment associated with $PM_{2.5}$ exposure was conducted for three age groups: infants (0–1 years), children (6–12 years), and adults (19–75 years (Morakinyo et al. 2017). According to Morakinyo et al (2017), the average daily inhalation dose was calculated using the following equation:

$$ADD_{inh} = \frac{CxIRxEFxED}{BWxAT}$$

$$ED = ET\ x\ EF\ x\ DE$$

$$HQ = \frac{ADD}{RFL}$$

Where *C* represents the $PM_{2.5}$ concentration (μg/m^3); *IR* is the average daily inhalation rate (m^3/day). *BW* denotes body weight (kg). *AT* is the averaging time for exposure (days). *ET* represents the exposure time (hours/day). *EF* is the exposure frequency (days/year), assumed to be 350 days/year, based on the assumption that individuals are absent from the study area for approximately 14 days per year (Morakinyo et al. 2017). *ED* denotes the exposure duration (days). *DE* represents the duration of exposure in years and was assumed to be 1, 12, and 30 years for infants, children, and adults, respectively (Morakinyo et al. 2017). Age-specific exposure parameters applied in the inhalation exposure assessment are summarized in Table 1.

RfL is the reference limit for $PM_{2.5}$ and PM_{10}, set at 25 μg/m^3 and 50 μg/m^3, respectively. A hazard quotient (HQ) $<$ 1 indicates no significant health risk in the study area, whereas HQ $>$ 1 suggests the presence of potential adverse health risks associated with particulate matter exposure (Morakinyo et al. 2017).

Table 1. Age-specific exposure parameters applied in the inhalation exposure assessment (Morakinyo et al. 2017).

Exposed group	Inhalation rate (m^3/day)	Body weight (kg)	AT (days)	ET (hours/days) Normal case	ET (hours/days) Worst case
Infant	9.1	11.3	365 (1x365)	1	24
Child	16.6	45.3	4200 (12x350)	6	24
Adult	21.4	71.8	10950 (30x365)	3	24

2. Results

2.1. Monthly Characteristics of Particulate Matter Concentrations

The annual average concentration of $PM_{2.5}$ was 79.75 μg/m^3, which is approximately 3.19 times higher than the allowable limit specified in QCVN 05:2023/BTNMT (25 μg/m^3). This significant exceedance indicates a serious level of fine particulate pollution, posing substantial risks to human health due to the ability of $PM_{2.5}$ to penetrate deep into the respiratory system. The average $PM_{2.5}$ concentrations observed in Hanoi were higher than those reported for Iași, Romania (16.92 ± 9.07 μg/m^3) (Galon-Negru et al. 2019), Bologna, Italy (19.68 ± 0.78 μg/m^3) (Sarti et al. 2015), and Shangri-La, China (13.32 ± 8.23 μg/m^3) (Yin et al. 2021). In contrast, the $PM_{2.5}$ concentrations measured in this study were substantially lower than those reported for Kanpur, India (102.8 ± 20.2 μg/m^3) (McNeill et al. 2020), Shandong Province, China (134 μg/m^3) (Zhang et al. 2018), Baoding City, China (155.66 μg/m^3) (Liu et al. 2018). $PM_{2.5}$ concentration observed in Thai Nguyen

City was higher than the values reported in Viet Tri, Ha Long, Hue, Da Nang (Anh et al. 2019).

Similarly, the annual mean concentration of PM_{10} reached 52.55 µg/m^3, slightly exceeding the national ambient air quality standard of 50 µg/m^3. Although the exceedance level of PM_{10} is lower compared to $PM_{2.5}$ it still reflects persistent air quality degradation throughout the year. The mean PM_{10} concentration observed in this study (53.26 µg/m^3) was substantially higher than those reported for Navarra, Spain (15.23 µg/m^3) (Aldabe et al. 2011) and Lecce, Italy (26.3 µg/m^3) (Cesari et al. 2012). However, it remained considerably lower than the levels documented in Northern China (182 µg/m^3) (Li et al. 2014) and Phitsanulok, Thailand (112.2 µg/m^3) (Srithawirat et al. 2016). PM_{10} concentration observed in Thai Nguyen City was higher than the values reported in Viet Tri, Ha Long, Hue, Da Nang (Anh et al. 2019).

Based on the monthly average concentrations of $PM_{2.5}$ and PM_{10} measured in Thai Nguyen Province, the results indicate a clear seasonal variation in ambient air quality and a strong influence of meteorological conditions **(**Figure 3**)**. When compared with the Vietnam National Technical Regulation on Ambient Air Quality (QCVN 05:2023/BTNMT), which specifies a 24-hour average limit of 50 µg/m^3 for $PM_{2.5}$ and 100 µg/m^3 for PM10, $PM_{2.5}$ concentrations exceeded the regulatory limit in most months of the year, particularly during the dry and cold season. Extremely high $PM_{2.5}$ levels were observed in January (160.32 µg/m^3) and December (132.43 µg/m^3), exceeding the standard by approximately 2.65 to more than three times, while substantial exceedances were also recorded in February, March, and November. During the rainy season (from May to October), $PM_{2.5}$ concentrations showed a decreasing trend; however, several months still exhibited values close to or slightly above the regulatory limit, suggesting the presence of persistent background emission sources such as traffic, industrial activities, and biomass burning.

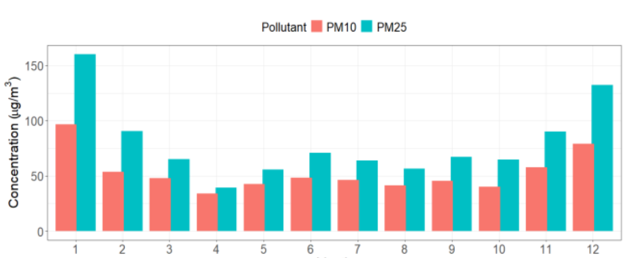

Figure 3. Monthly variations in average $PM_{2.5}$ and PM_{10} concentrations.

In contrast, PM_{10} concentrations ranged from 34.04 to 96.68 µg/m^3 and remained below the QCVN 05:2023/BTNMT limit throughout the year, although higher values were observed in the winter months, particularly in January and December. This seasonal pattern highlights the different behaviors of fine and inhalable particles, with $PM_{2.5}$ being more sensitive to unfavorable meteorological conditions. In Thai Nguyen, winter conditions are characterized by low rainfall, weak wind speeds, and frequent temperature inversions, which limit atmospheric dispersion and promote the accumulation of fine particles. Conversely, during the rainy season, increased precipitation and stronger atmospheric mixing enhance wet deposition and dilution processes, leading to lower particulate matter concentrations.

2.2. Assessment of the Health Risk Level Associated with Particulate Matter Exposure

The results of the Hazard Quotient (HQ) assessment presented in Table 2 reveal clear differences between the normal case and the worst-case scenario for the three studied population groups, including infants, children, and adults, when exposed to fine particulate matter ($PM_{2.5}$) and inhalable particulate matter (PM_{10}).

Table 2. Hazard quotients for normal and worst-case exposure scenarios to PM_{10} and $PM_{2.5}$.

Exposed group	Normal case		Worst case	
	$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_{10}
Infant	0.10	0.03	2.46	0.81
Child	0.28	0.09	1.12	0.37
Adult	0.11	0.04	0.91	0.30

Under normal conditions, all HQ values are below the safety threshold (HQ < 1), indicating negligible health risks for all age groups. Specifically, for $PM_{2.5}$, children exhibit the highest HQ value (0.28), followed by adults (0.11) and infants (0.10). Although all values remain within the safe range, this pattern highlights a notable trend in which children are more sensitive than adults, with HQ values approximately 2.5 times higher. This can be attributed to children's physiological characteristics, including a higher breathing rate relative to body weight, an immature respiratory system, and typically longer durations of outdoor activity compared to adults. For PM_{10}, HQ values in the normal case are considerably lower, with the highest value reaching only 0.10 in children, indicating that inhalable particles pose a lower health risk than fine particles under normal conditions.

However, the situation changes dramatically under the worst-case scenario. HQ values increase sharply, particularly among infants and children. For infants, the HQ for $PM_{2.5}$ in the worst case reaches 2.46, exceeding the safety threshold by nearly 2.5 times and representing a 24-fold increase compared with the normal case. This result indicates that infants face a very high health risk when air quality deteriorates. Similarly, the HQ for PM_{10} in infants increases from 0.03 to 0.81, reflecting a comparable 24-fold rise. This substantial increase underscores the particular vulnerability of infants to air pollution, as their immune and respiratory systems are not yet fully developed.

For children, although the magnitude of increase is lower than that observed in infants (approximately fourfold), the HQ for $PM_{2.5}$ in the worst case still reaches 1.12, exceeding the safety threshold by about 12 %. This implies that under severe pollution conditions, children are at risk of adverse health effects from $PM_{2.5}$ exposure. The HQ for PM_{10} in children also rises to 0.37; while it remains below the safety threshold, it is significantly higher than in the normal case. Adults appear to be more resilient, with worst-case HQ values of 0.91 for $PM_{2.5}$ and 0.30 for PM_{10}, both remaining below the safety threshold despite increasing by approximately eight times compared with normal conditions.

Another noteworthy finding is the clear difference in hazard levels between $PM_{2.5}$ and PM_{10}. In the normal case, HQ values for $PM_{2.5}$ are approximately 2.7–3.0 times higher than those for PM_{10} across all age groups. In the worst case, only $PM_{2.5}$ exceeds the safety threshold for infants and children, whereas PM_{10} maintains HQ values below 1 for all three groups. This observation is consistent with established scientific understanding of the characteristics of these particles. $PM_{2.5}$, with an aerodynamic diameter smaller than 2.5 µm, can penetrate deeply into the alveoli and even enter the bloodstream, leading to more severe health impacts (Kim et al. 2015; Wu et al. 2018; Suriyawong et al. 2023). In contrast, PM_{10} is primarily deposited in the upper respiratory tract and has lower toxicity, resulting in comparatively lower health risks (Kelly and Fussell 2012).

An analysis of the increase in HQ values from the normal case to the worst case presents a concerning picture of age-specific vulnerability. Infants show the highest increase-24-fold for both $PM_{2.5}$ and PM_{10}, indicating extreme sensitivity to changes in air quality. Adults exhibit an eightfold increase, while children show an intermediate increase of approximately fourfold. These differences can be explained by variations in physiological and behavioral factors among age groups. Infants have the highest respiration rate relative to body weight, an immature immune system, and spend most of their time in passive environments; therefore, when air quality deteriorates, they cannot protect themselves compared with adults (Fleming et al. 2011).

Based on this analysis, several important conclusions and recommendations can be drawn. Under normal conditions, ambient air quality is assessed as safe for all age groups, with HQ values below 1. However, under the worst-case scenario, infants face very high health risks, with HQ of $PM_{2.5}$ reaching 2.46, and thus require special protection and complete avoidance of exposure during poor air quality episodes. Children also warrant particular attention, as their HQ values exceed the safety threshold; outdoor activities should be restricted, and protective measures such as mask use should be implemented when necessary. Although adults demonstrate greater resilience, caution is still required when HQ values approach the threshold of 1.

From an environmental management and public health perspective, priority should be given to controlling and reducing $PM_{2.5}$, as this pollutant exhibits substantially higher toxicity than PM_{10} and is the primary driver of threshold exceedances under worst-case conditions (Park et al. 2018; Jakhar et al. 2025). Early warning systems and clear public guidance should be established when the Air Quality Index (AQI) increases, with specific recommendations for households with young children. During periods of severe pollution, the use of appropriate masks, indoor air purifiers, and the limitation of outdoor physical activities should be encouraged, particularly for infants and children. This study highlights the critical importance of maintaining good air quality to protect public health, especially for the most vulnerable population groups.

One limitation of this study is that the health risk assessment was based on air quality data from a single year, which may not fully capture long-term variations in pollutant concentrations and emission patterns. Additionally, seasonal meteorological conditions and spatial variability of air pollutants may introduce uncertainties in the estimation of long-term exposure and associated health risks.

3. Conclusion

This study analyzed the temporal and monthly variations of ambient $PM_{2.5}$ and PM_{10} concentrations in Thai Nguyen City and quantitatively assessed the associated non-carcinogenic health risks for different population groups. Based on the obtained results, ambient air pollution in Thai Nguyen City is characterized by a high level of fine particulate matter contamination, particularly during the dry and cold season. Monthly average $PM_{2.5}$ concentrations exceeded the national regulatory limit (QCVN 05:2023/BTNMT) in most months of the year, with extremely severe pollution episodes recorded in January and December, when concentrations were more than 2.6 to over three times higher than the permissible level. These findings indicate that $PM_{2.5}$ pollution in Thai Nguyen is not occasional but persistent and seasonally aggravated, reflecting the combined effects of unfavorable meteorological conditions and continuous emission sources such as traffic, industrial activities, and biomass burning. In contrast, PM_{10} concentrations remained within regulatory limits throughout the year, suggesting that fine particles represent the dominant air quality concern in the study area. Health risk assessment results further demonstrate that, under normal conditions, exposure to particulate matter poses negligible risks for all age groups. However, under worst-case scenarios, $PM_{2.5}$ exposure leads to unacceptable health risks for infants and children, with Hazard Quotient values exceeding the safety threshold, whereas adults remain below the threshold. Overall, $PM_{2.5}$ consistently contributes more significantly to health risks than PM_{10} due to its higher toxicity and greater penetration into the respiratory system.

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