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Integrated Quality Assessment of Windrow-Composted Municipal Solid Waste Using Fertilizer Index, Clean Index, and Multivariate Statistical Analysis: A Case Study from Hyderabad, India

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Abstract: This research evaluates the quality of windrow-composted municipal solid waste based on the fertilizer index, clean index, and multivariate statistical for sustainable waste management and resource recovery. To achieve the objective, 25 WC samples were collected from the composting plant of the Greater Hyderabad Municipal Corporation (GHMC), Hyderabad, India. The investigation evaluated physicochemical characteristics, heavy metals, and nutrient content in alignment with the development pathway for sustainable resource recovery. Heavy metal concentrations were determined for the assessment of possible environmental risks. Compost quality assessment employed the fertilizer index (FI) and clean index (CI) measurements that combine nutrient value and contamination levels. The FI values ranged from 3.35 to 4.30, while CI values ranged from 3.20 to 4.00. Based on the combined FI-CI classification, 24 samples were classified as Class C (good quality) and one sample as Class D (medium quality). Statistical analysis showed notable correlations between nutrient components and maturity parameters, demonstrating how organic matter stabilization affects compost quality. Various statistical approaches, including multiple linear regression, Pearson correlation analysis, and principal component analysis (PCA), were used to examine relationships and patterns among the measured variables. The results showed that the WC of MSW in GHMC, Hyderabad, produces compost with optimal nutrient levels and permissible heavy metal levels. This study provides one of the first integrated FI-CI and multivariate assessments of MSW compost quality in Hyderabad and enables a platform for sustainable quality assessment of windrow-composted municipal solid waste.

Keywords: windrow composting; municipal solid waste; hyderabad; fertilizer index; clean index; multivariate analysis

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1. Introduction

Rapid urbanization and population growth have significantly increased MSW generation in metropolitan cities [1]. Managing a large volume of waste in an environmentally sustainable manner has become a major challenge for municipal authorities [2]. In many developing countries, a substantial fraction of MSW is composed of biodegradable organic materials, which provide an opportunity for conversion into valuable products through biological treatment methods [3]. Among the various waste management processes, composting has gained considerable attention as an efficient and eco-friendly process for converting organic waste into stable organic amendments that can improve soil fertility [4,5]. Windrow composting (WC) is widely adopted methods for the treatment of MSW due to its simple operation, economical, and adaptability to large-scale waste management systems [6,7]. In this process, organic waste materials are arranged in elongated piles known as windrows and periodically turned to ensure proper aeration and microbial activity. The biological decomposition occurring during composting leads to the stabilization of organic matter, reduction of pathogens, and production of a humus-like material that can be used in agricultural soils [8]. However, the quality of compost generated from MSW depends on the properties of the composting conditions, material input, and management practices.

MSW-based compost offers various agricultural advantages, but the quality and safety continue remain critical concerns [9]. Elements like zinc (Zn), lead (Pb), cadmium (Cd), copper (Cu), nickel (Ni), and chromium (Cr) may accumulate in compost when contaminated materials are present [10]. A major challenge involves heavy metal contamination from mixed municipal waste sources. Excessive metal levels create environmental and health risks when used in soil [11]. Therefore, analysing nutrient content and the contamination level is important prior to utilizing compost as a soil enhancer [12].

Factors including pH, moisture content, total organic carbon (TOC), electrical conductivity (EC), N, P, K, and the carbon-to-nitrogen (C/N) ratios offer important insights into the decomposition process and nutrient supply [13]. These various physicochemical indicators are employed to determine compost maturity and stability. Integrated indices incorporating various parameters have been established for comprehensive quality assessment. The FI represents a commonly used metric for evaluating compost fertility potential, whereas the CI measures heavy metal pollution against regulatory standards [14]. Utilizing the FI and CI enables more thorough compost quality classification in terms of its suitability for agricultural applications [15,16].

Recently, the application of multivariate statistical methods to environmental research has significantly increased, improving the understanding of complex relationships among several factors [17]. The techniques, including correlation analysis, multiple linear regression, and principal component analysis (PCA), are effective for establishing primary factors that determine compost quality and simplifying complex datasets [18]. These techniques allow researchers to determine how physical-chemical properties, nutrient composition, and heavy metal levels combinedly impact compost quality and sample variation [19].

As a major Indian metropolitan city, Hyderabad generates large MSW volumes due to accelerated urbanization and increasing population density. GHMC handles waste management through multiple processing centers, including windrow composting facility. Though WC serves as an efficient biodegradable waste treatment process, rigorous compost quality evaluation from these installations is necessary for proper agricultural applications [20]. While composting systems are progressively implemented in urban waste management programs, evaluation combining nutrient assessment, heavy metal evaluation, and statistical analysis remain limited for Indian municipalities [21]. For Hyderabad, particularly, detailed investigations examining WC from MSW using qualitative parameters and multivariate statistical techniques are limited, and an insightful understanding is needed for industrial, municipal, and scientific communities. Understanding compost quality variability and recognizing key elements affecting nutrient value and metal contamination are crucial for improving compost management and utilization approaches. However, few studies have combined FI, CI, and multivariate statistical techniques for through MSW compost quality evaluation in Indian urban metropolitan contexts, especially in Hyderabad.

This study evaluates windrow-compost samples collected from the MSW processing facility operated under the GHMC. The objectives were to (i) characterize physicochemical properties and nutrient composition, (ii) quantify selected heavy metals and compare them with applicable limits, (iii) assess compost quality using the FI and CI, and (iv) explore relationships among measured variables using Pearson correlation and PCA. Previous studies have applied FI and CI to MSW compost; therefore, the novelty of the present work is not the introduction of new indices. Rather, it lies in their combined application to 25 finished windrow compost batches from a centralized facility handling unsegregated municipal waste, alongside a multivariate examination of the measured quality variables. This integrated, facility-specific assessment provides a structured way to interpret nutrient-related quality

and selected metal contamination together. The findings should be viewed as a case study and a basis for further seasonal and multi-facility validation, rather than as a universally validated certification framework.

2. Materials and Methods

2.1. Study Area and Compost Sample Collection

Compost samples were collected from the centralized Integrated MSW facility at Jawaharnagar, Hyderabad, India. The facility processes incoming unsegregated municipal solid waste through a structured mechanical pre-sorting chain, where waste is initially passed through primary 100-mm mechanical trommel screens to separate the organic-rich undersized fraction from larger combustible materials destined for refuse-derived fuel (RDF) as shown in Figure 1.

The separated organic fraction is then subjected to aerobic windrow composting on a specialized, impermeable concrete platform spanning approximately 28,125 m^2. The primary windrow phase runs for an active biological decomposition cycle of approximately 26 days. Aeration and porosity are sustained via mechanical turning units operated at a fixed frequency of every 6th day from windrow formation, completing exactly 4 full turnings during the active cycle. Following the windrow stage, the decomposed mass is transferred to a covered monsoon shed for 7 to 10 days of natural drying and moisture reduction. The dried material undergoes final mechanical refinement through sequential 35-mm and 16-mm trommel screens to isolate heavy fractions, glass, and inert debris. A total of twenty-five (25) representative composite samples were systematically drawn from the final stabilized, refined compost batches prior to packaging. The sampling was conducted over a structured timeline to capture operational batches ready for field application, ensuring the representativeness of the final product. These biodegradable components are processed through WC systems to produce compost for agricultural and landscaping applications [22]. Batch-level sampling was used to capture variation among finished product batches at the facility, but the single-facility design and absence of seasonal coverage limit broader representativeness. These constraints are acknowledged in the study limitations.

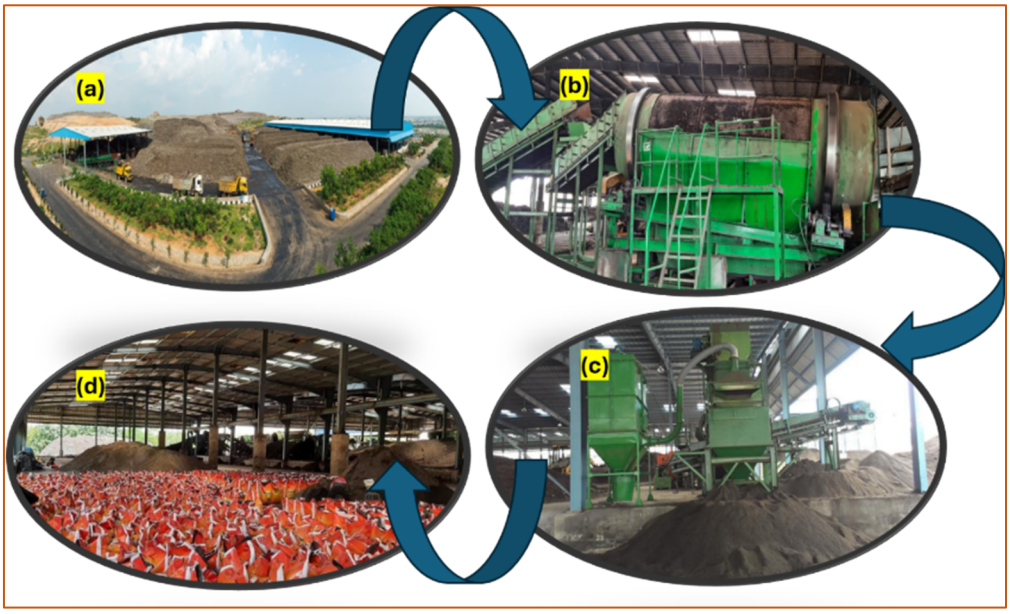

Figure 1. The composting process adopted at the integrated MSW processing plant, illustrating key operational stages: (**a**) WC under open platform conditions, (**b**) Coarse screening for removal of large inert materials, (**c**) Fine screening to obtain uniform compost, and (**d**) Packaging of the stabilized product.

2.2. Physicochemical Characterization

The physicochemical properties of the compost samples were determined using standard analytical procedures commonly applied in compost quality assessment [23]. The pH of the compost was measured using a digital pH meter in a compost–water suspension prepared at a ratio of 1:10 (*w*/*v*). EC was measured using a conductivity meter in the same extract to evaluate the soluble salt content of the compost. The moisture content of the samples was determined by oven drying a known weight of compost at 105 °C until a constant weight was obtained. TOC was determined by performing standard organic carbon determination technique and the Kjeldahl digestion method [24] is used for analysing total nitrogen (N). Major nutrient analysis was performed after subjecting

compost samples to acid digestion using spectrophotometric methods for P analysis and photometry for measurement of K. Standard analytical methods were applied for all analyses as shown in Table S1. The resulting C/N ratio, calculated from carbon and nitrogen values, was considered as an indicator of compost maturity and organic matter stabilization. The respiration rate was also included as a stability-related parameter. Because maturity and stability are method-dependent characteristics, these parameters were interpreted together with other physicochemical properties and compared with criteria reported in previous compost-quality studies [25].

2.3. Determination of Heavy Metal Concentrations

Compost samples were analyzed for heavy metal concentrations to determine potential contamination and environmental concerns associated with compost use in soil applications. Dried compost weighing approximately 1 g was processed through acid digestion with concentrated nitric acid and additional reagents to ensure total metal dissolution. The solution was filtered and diluted with deionized water after digestion. The concentrations of heavy metals were compared with regulatory limits to evaluate the suitability for agricultural applications. The analytical scope of this study was limited to Zn, Cu, Cd, Pb, Ni, and Cr. Mercury (Hg) and arsenic (As) were not included in the analytical programme, and no concentrations for these elements are available for comparison. Their omission is therefore treated as a limitation.

2.4. Fertilizing Index (FI) and Clean Index (CI)

The FI and CI indices were used as composite interpretation tools to summarize different dimensions of compost quality. FI combines nutrient-related parameters (TOC, N, P, K, and C/N ratio) into a single fertility-oriented score, while CI combines the measured heavy-metal results relative to the scoring criteria into a cleanliness-oriented score. Their main value in this study is to provide a common classification framework in which nutrient-related quality and selected-metal contamination can be considered together, rather than to provide information independent of the underlying measurements. The indices are consequently interpreted alongside the individual physicochemical and metal concentrations [26]. The scoring criteria used are provided in Tables S2 and S3.

2.5. Multivariate Statistical Analysis

Statistical analyses were performed to analyze and understand the relationships among physicochemical parameters, heavy metal concentrations, and nutrient content [27]. Correlation analysis was performed to identify the relationships among compost characteristics and to determine how various parameters affect compost quality. Pearson correlation coefficients were determined by using the data of the twenty-five samples.

Multiple linear regression analysis was performed to examine the statistical relationship between FI and its constituent parameters (Table S1–S3), namely TOC, N, P, K, and C/N ratio. Since these variables are directly incorporated into the calculation of FI, the regression analysis was treated as a descriptive assessment of their statistical contribution to the composite index rather than as an independent predictive model. The coefficient of determination (R^2) adjusted R^2, regression coefficients, *p*-values, and residuals were examined to characterize the fitted relationship. Detailed regression results are provided in Table S4. PCA was subsequently conducted to identify major patterns and sources of variation within the multivariate dataset, while the PCA biplot was used to visualize relationships among variables and compost samples. All statistical analyses and graphs were performed using OriginPro 2023.

3. Results and Discussion

3.1. Moisture Content Distribution and Variation of pH and EC

Microbial activity and the organic matter stabilization during composting are significantly affected by moisture content [28]. The moisture distribution among the twenty-five compost samples and the FCO standard is illustrated in Figure 2, with the comprehensive values summarized in Table 1. The boxplot demonstrates the moisture content variation, where the box represents the interquartile range and the whiskers show the data spread up to 1.5 times the interquartile range. The results reveal moderate variability in moisture levels across the samples. The median moisture value falls within the recommended optimal range for mature compost, indicating that samples achieved appropriate drying in the final stage of WC. A single outlier, denoted by the diamond symbol, reveals that one sample retained comparatively higher moisture content relative to the others. Such variations are attributed to differences in aeration practices, turning frequency, and environmental circumstances of windrow piles. The moisture content indicates successful stabilization, with moisture levels that are suitable for storage.

Table 1. Physicochemical Properties of Compost Samples (n = 25).

Parameter	Mean ± SD	CV (%)
Moisture (%)	20.21 ± 2.00	9.91
pH	7.39 ± 0.18	2.47
EC (dS m^{-1})	4.33 ± 0.44	10.17
TOC (%)	18.26 ± 4.26	23.33
Volatile Solids (%)	32.87 ± 7.67	23.33

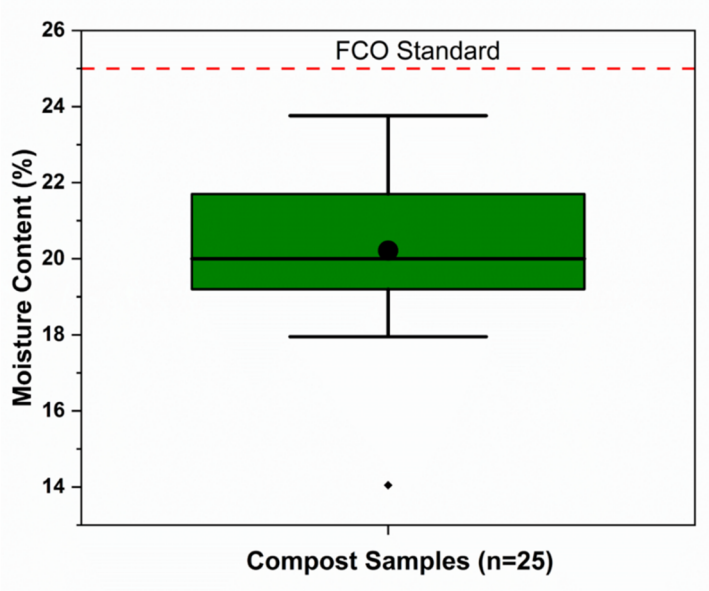

Figure 2. The moisture content distribution of compost samples (n = 25).

Figure 3 illustrates the pH and EC values among the compost samples with detailed results reported in Table S1. The compost samples showed neutral pH levels, demonstrating that organic decomposition occurred successfully during the compost process. Neutral pH is desirable because it promotes microbial activity and enhances the bioavailability of nutrients in soil following compost incorporation. EC measures the quantity of dissolved salts present in compost. The EC levels remained within acceptable range, reducing the risk of salt induced plant damage. Variations in EC between samples reflects differences composition of input, particularly the balance between organic and inorganic components in MSW. The results are in acceptable range to standard values of mature MSW compost [29]. The neutral pH combined with moderate EC demonstrate that WC municipal compost processes achieve suitable chemical properties for agricultural applications.

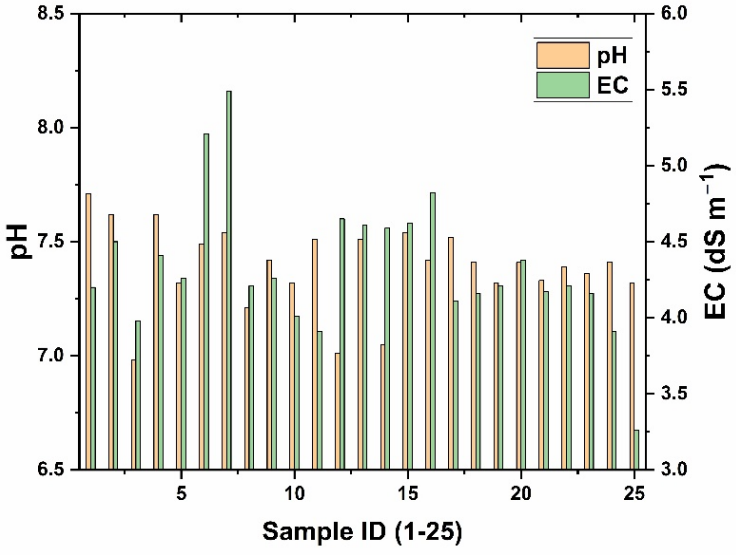

Figure 3. The variation of pH and EC compost from municipal composting plant.

3.2. Distribution of Heavy Metal and Comparison with Regulatory Standards

Figure 4 displays the concentrations of heavy metals (Zn, Cu, Ni, Cd, Pb, and Cr) of compost samples, with the complete data is reported in Table 2. The boxplot analysis reveals significant variation in metal concentrations of compost samples. Zn and Cu exhibited higher concentrations relative to the other metals, a characteristic pattern in municipal waste produced compost resulting from metal present in household items and decomposed organic residues. Conversely, Cd and Pb were of low concentrations in most samples, which indicate successful reduction by dilution and stabilization process during composting. The boxplot dispersion shows moderate heterogeneity among samples due to variation in the waste composition. The overall metal concentration distribution indicates that heavy metals were appropriately maintained within permissible limits in the compost [30,31].

Table 2. Heavy Metal Concentrations in Compost Samples.

Metal	Mean ± SD (mg kg^{-1})	CV (%)	Permissible Limit
Zn	279.08 ± 132.89	47.62	1000
Cu	122.10 ± 63.82	52.27	300
Cd	1.77 ± 0.34	19.08	3
Pb	43.49 ± 17.19	39.52	150
Ni	17.44 ± 4.77	27.35	50
Cr	17.82 ± 7.41	41.58	100

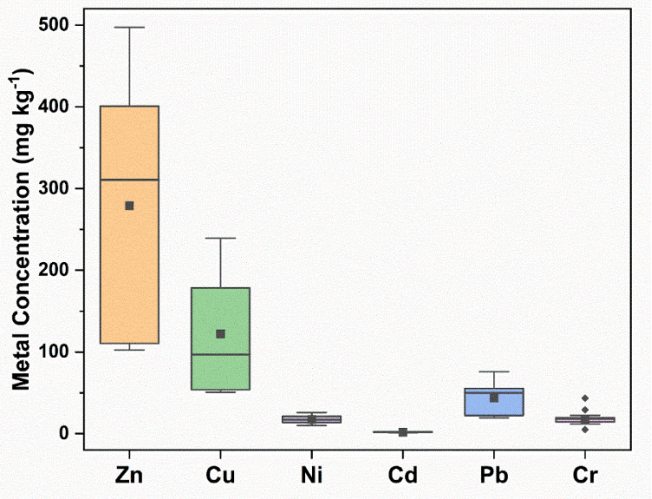

Figure 4. The heavy metal distribution (Zn, Cu, Ni, Cd, Pb, and Cr) in compost samples (n = 25). The box indicates the interquartile range (25–75%), the horizontal line marking the median, the filled square indicating the mean, and whiskers extending to 1.5 × IQR.

The measured concentrations of Zn, Cu, Cd, Pb, Ni, and Cr were compared with the permissible limits cited for the Fertilizer Control Order (FCO), India, as illustrated in Figure 5. The mean concentrations reported in Table 2 were below the corresponding limits. This indicates compliance for the six metals measured at the level of the reported summary statistics; it does not establish that every sample complied unless individual sample results are checked against each limit. It also does not address Hg, As, pathogens, phytotoxicity, or crop response. Accordingly, the results support a favourable preliminary assessment of selected-metal concentrations, rather than a complete determination of biological or agronomic safety.

The distribution of heavy metal concentrations followed the decreasing order of Zn > Cu > Pb > Cr > Ni > Cd. Although the mean concentrations stay within the regulatory thresholds stipulated by the Fertilizer Control Order (FCO, India), the data exhibits notable variations. This statistical dispersion is directly tied to the low conversion yield of incoming material to finished compost (varying around 5% to 7% at this centralized facility due to high mixed inert fractions). Because the processing facility treats unsegregated municipal waste, the presence of household batteries, cosmetics, plastics, and electronic micro-debris in the raw feedstock drives up the variance of metals like zinc (Zn) and copper (Cu). This underscores the critical need to look beyond simple binary 'pass/fail' regulatory compliance and investigate the source dynamics of centralized municipal composting.

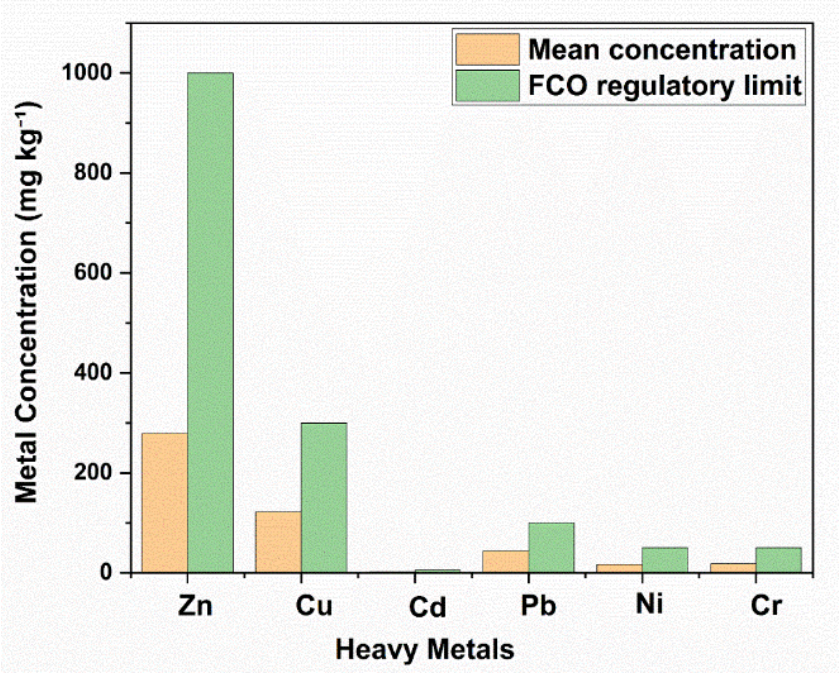

Figure 5. Comparison of mean heavy metal concentrations in compost samples with permissible limits specified by the Fertilizer Control Order (FCO), India, & MSW(M&H) 2016 and 2026.

3.3. FI Evaluation

The fertilizing potential of the compost samples was evaluated using the FI, which integrates nutrient parameters including TOC, total N, P, K, and the C/N ratio as shown in Table 3. The calculated FI values ranged from 3.35 to 4.30 (Table 4).

The distribution of FI values for the compost samples is shown in Figure 6, and the individual FI and CI values are listed in Table 4 and mean of FI and CI in Table 5. The boxplot shows that FI values are concentrated within a limited range, indicating uniform nutrient properties among the compost samples. Most samples exhibited FI values within the range associated with moderate to high fertilizing potential. The median value observed in the figure indicates that most of the compost products possess a favourable nutrient composition suitable for agricultural use. These results demonstrate that WC of MSW can produce compost with appreciable fertilizing potential when appropriate management practices are followed [32].

Table 3. Nutrient composition and maturity indicators of compost samples.

Parameter	Mean ± SD	CV (%)
Total N (%)	1.32 ± 0.24	17.87
Total P (%)	0.28 ± 0.04	15.36
Total K (%)	0.65 ± 0.43	65.52
C/N Ratio	14.44 ± 4.19	29.00
Respiration Rate	0.66 ± 0.29	44.17

The C/N ratio and respiration rate provide additional information on the maturity and stability of the finished compost. The mean C/N ratio was 14.44 ± 4.19, indicating substantial decomposition of readily biodegradable organic matter and falling within the range commonly reported for mature or stabilized compost [33]. However, C/N ratio thresholds can vary with feedstock composition and composting conditions and should therefore be interpreted together with other maturity indicators. The mean respiration rate was 0.66 ± 0.29 and was considered as a supporting indicator of biological stability, since microbial respiration generally decreases with the stabilization of readily degradable organic matter [34]. Because numerical respiration thresholds depend on the analytical method, incubation conditions, duration, and reporting units, the present value was interpreted qualitatively rather than against a specific threshold. Overall, the C/N ratio and respiration-rate measurement, together with the other physicochemical characteristics, support the interpretation that the compost had undergone substantial stabilization before sampling.

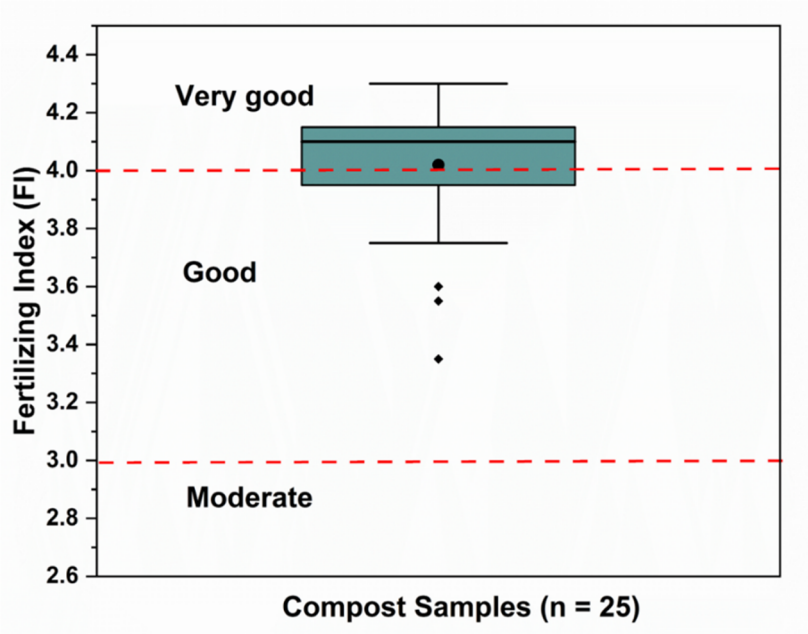

Figure 6. Distribution of FI values for compost samples (n = 25). The box represents the interquartile range (25–75%), the horizontal line indicates the median, and whiskers represent the range within 1.5 × IQR.

Table 4. FI and CI of compost samples.

Sample	FI	CI	Compost Class
S1	4.1	3.4	C
S2	4.1	3.53333	C
S3	4.05	3.6	C
S4	3.35	3.33333	D
S5	3.85	3.2	C
S6	4.1	3.33333	C
S7	3.55	3.73333	C
S8	3.95	3.53333	C
S9	4.1	3.53333	C
S10	3.75	3.6	C
S11	4.1	3.33333	C
S12	4.05	3.46667	C
S13	4.05	3.4	C
S14	4.3	3.53333	C
S15	4.3	3.53333	C
S16	3.6	3.53333	C
S17	3.85	3.53333	C
S18	4.3	3.86667	C
S19	4.15	3.86667	C
S20	4.15	3.86667	C
S21	4.15	3.86667	C
S22	4.15	3.86667	C
S23	4.15	3.86667	C
S24	4.15	3.86667	C
S25	4.15	4	C

Note: C—Good quality. High fertilizing potential and medium heavy metal content. D—Medium quality. Medium fertilizing potential and medium heavy metal content.

Table 5. Statistical summary of FI and CI values for compost samples (n = 25).

Index	Mean	Standard Deviation	Minimum	Maximum
FI	4.02	0.238	3.35	4.3
CI	3.608	0.20	3.2	4.0

3.4. FI-CI Compost Quality Classification

A combined assessment of nutrient value and heavy metal contamination was performed using the FI and CI framework. The FI is a weighted composite indicator that evaluates the agronomic value of compost based on key fertility parameters, including TOC, N, P, K and C/N ratio. Higher Fi values indicate greater nutrient availability and fertilizing potential. In contrast, the CI is weighted index that assesses compost safety by integrating the concentrations of heavy metals relative to their permissible limits; higher CI value represents lower contamination risk and better environmental suitability.

The relationship between FI and CI values is presented in Figure 7, where each point represents a compost sample. The FI–CI diagram allows the categorization of compost samples based on their fertilizing potential and degree of metal contamination, with results indicating that samples fall with in the zone of elevated fertility and minimal metal hazard, marked by substantial values and Positive CI scores. The result of the distribution indicates that compost from MSW maintains an equilibrium between nutritional content and is environmental safety [35]. The integrated FI-CI approach provides a comprehensive assessment of compost quality by considering agronomic benefits and potential contamination risks.

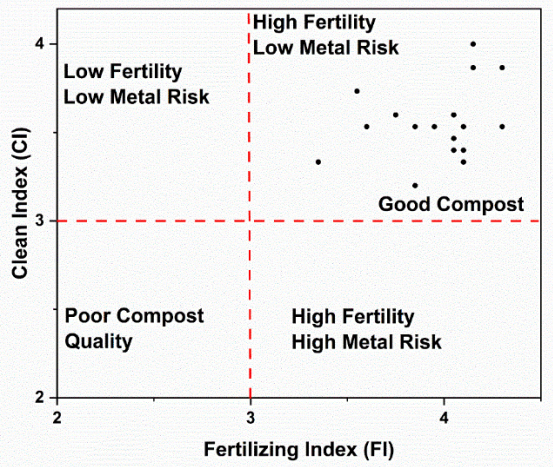

Figure 7. The relationship between FI and CI, providing insight into compost quality classification (n = 25), heavy metal safety and fertilizing potential of compost samples.

3.5. Clean Index Distribution

The distribution of CI values of the compost samples analysed is shown in Figure 8, with detailed results are tabulated in Table 5. The CI values ranged between 3.2 to 4.0, with an average of 3.608. According to the compost quality standards, CI greater than 4 indicates less contamination risk and good compost. The CI is a weighted parametric indicator derived from the concentrations of heavy metals relative to their prescribed threshold limits. Higher CI values indicate lower contamination and greater environmental safety. However, CI < 4 does not necessarily imply that the compost is unsuitable for agricultural use. It indicates a comparatively higher metal content and places the compost in the lower quality category within the FI-CI classification framework. The compost suitability should be determined using the combined interpretation of FI and CI rather than CI alone. Among the 25 samples analysed, 24 were classified as Class C and one as Class D based on the combined FI–CI assessment. These results indicate that the compost samples exhibited acceptable quality with respect to the evaluated contamination parameters. The high CI values are corresponding with the low heavy metal concentrations detected, suggesting that the compost processes effectively in reducing contamination mobility while keeping trace metal concentration within acceptable limits. [26].

The combined FI-CI classification provides an integrated indication of nutrient-related fertility characteristics and selected heavy-metal cleanliness of the compost. In the present study, 24 samples were classified as Class C based on the adopted FI-CI criteria, indicating comparatively favourable nutrient characteristics and acceptable levels of the assessed heavy metals. However, this classification should not be interpreted as direct evidence of crop suitability or agronomic performance. Actual agricultural suitability also depends on factors such as seed germination response, phytotoxicity, pathogen safety, soil compost interactions, and plant growth performance, which were not evaluated in the present study.

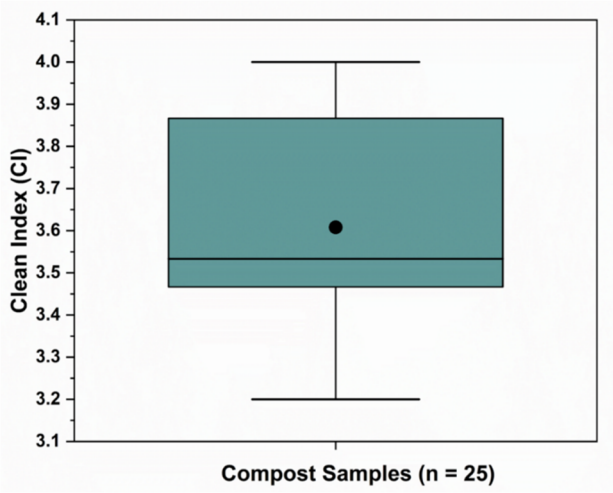

Figure 8. Distribution of CI values for compost samples (n = 25). The box represents the interquartile range (25–75%), the horizontal line indicates the median, and the whiskers represent the range within 1.5 × IQR.

3.6. Correlation Analysis of Compost Parameters

A Pearson correlation analysis was performed to examine the relationships among physicochemical properties, heavy metals, nutrient composition, and compost quality indices (FI and CI), as presented in Figure 9. The correlation heatmap shows the Pearson correlation coefficients among the measured variables. Strong positive correlations were observed among several nutrient-related parameters, including organic carbon, N, P, and K, reflecting their interrelated contribution to compost fertility. The heavy metal variables showed different correlation patterns with the nutrient parameters, indicating variations in their distribution among the compost samples. The positive associations between FI and nutrient-related parameters are consistent with the mathematical construction of the FI, which incorporates these variables into the index. Similarly, the relationship between CI and heavy metal concentrations reflects the basis of the CI calculation. Therefore, these correlations are interpreted as relationships among the measured variables and derived indices rather than as independent evidence of causal effects.

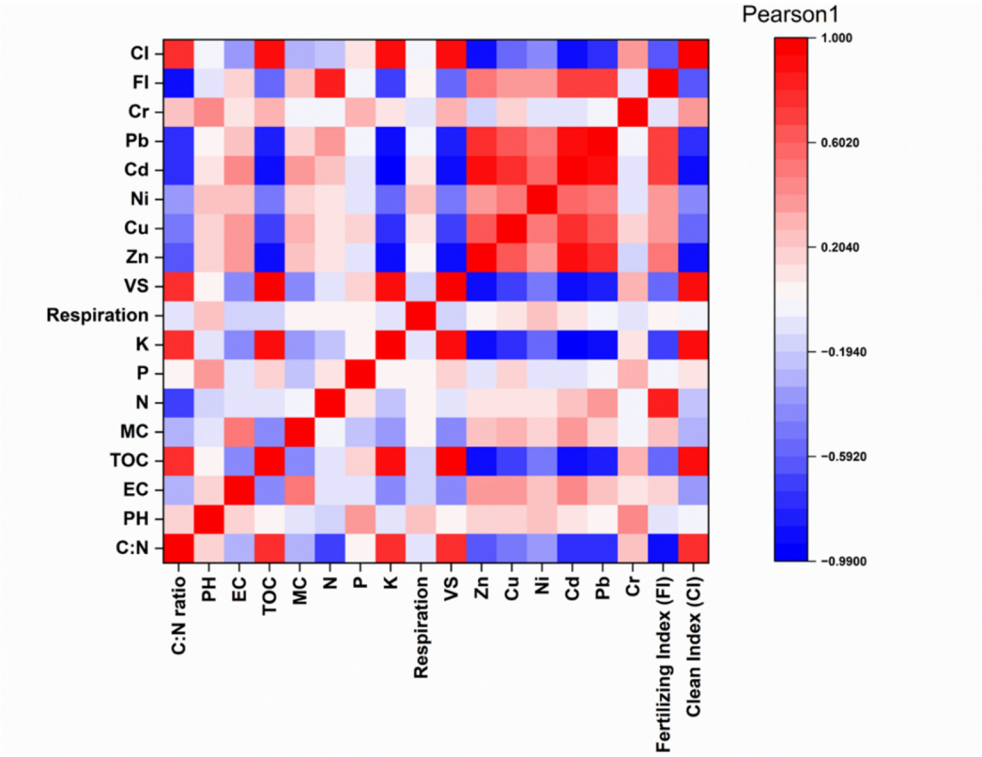

Figure 9. Pearson correlation heatmap showing the relationships among physicochemical properties, nutrient parameters, heavy metals, and quality indices (FI and CI) of compost samples (n = 25), colours indicating Pearson correlation coefficients ranging from −1 to +1.

3.7. Multiple Linear Regression Analysis of FI

Multiple linear regression analysis was performed to examine the statistical relationships between the Fertilizer Index (FI) and its constituent nutrient-related parameters (TOC, N, P, K, and C/N ratio) [36,37]. Because these variables are directly incorporated into the calculation of FI, a strong statistical association between FI and the selected parameters is expected. Therefore, the regression analysis is interpreted here as a descriptive assessment of the relative contribution and association of the constituent parameters with FI rather than as an independent predictive model.

The multiple linear regression relationship used in the analysis Equation (1) was expressed as:

$$FI = \beta_0 + \beta_1 (TOC) + \beta_2 (N) + \beta_3 (P) + \beta_4 (K) + \beta_5 (C/N) \quad (1)$$

where β_0 is the intercept and β_1–β_5 are regression coefficients associated with the respective parameters.

The relationship between the calculated FI values and the regression estimates is presented in Figure 10 and Table S4. The coefficient of determination (R^2) was greater than 0.912, indicating a strong statistical association between FI and the selected constituent parameters. However, this high R^2 should be interpreted with caution because TOC, N, P, K, and C/N are themselves components of the FI calculation. Consequently, the high degree of agreement does not represent independent predictive validation of FI and should not be interpreted as evidence of external predictive capability.

The residual distribution shown in Figure 11 indicates the deviations between the calculated FI values and the regression estimates. These residuals are presented as a diagnostic description of the fitted relationship rather than as evidence of predictive accuracy. Overall, the regression analysis complements the FI framework by demonstrating the statistical contribution of its constituent parameters, while the independent assessment of compost quality is provided through the FI-CI classification, Pearson correlation analysis, and PCA.

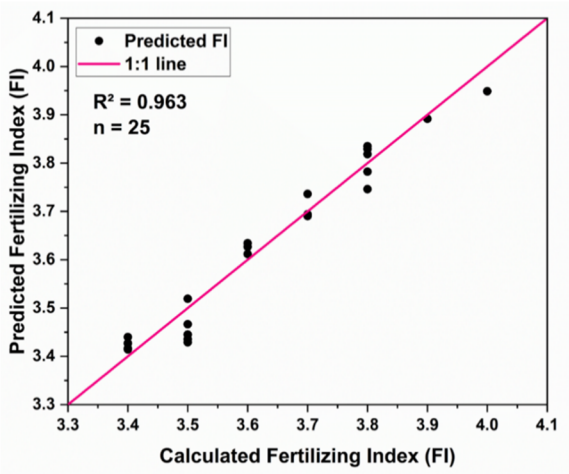

Figure 10. Comparison between calculated FI values and FI estimates obtained from the multiple linear regression analysis using TOC, N, P, K, and C/N ratio.

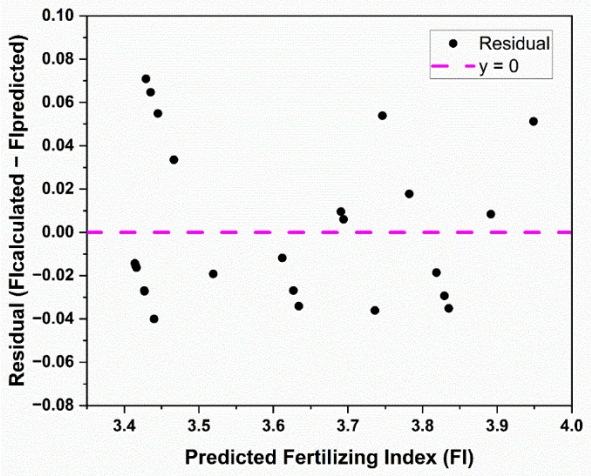

Figure 11. Distribution of residuals versus FI estimates obtained from the multiple linear regression analysis.

Figure 12 shows the relative regression coefficients of the physicochemical parameters included in the FI calculation. Nitrogen exhibited the largest coefficient magnitude among the selected variables, while P and K also showed appreciable statistical contributions. TOC and the C/N ratio exhibited comparatively smaller coefficients under the present regression formulation. These differences reflect the statistical weighting and variation of the constituent parameters within the FI framework and should not be interpreted as independent evidence that nitrogen is the primary determinant of compost fertilizing potential. Rather, the analysis demonstrates how the constituent nutrient parameters are statistically associated with the composite FI under the present dataset.

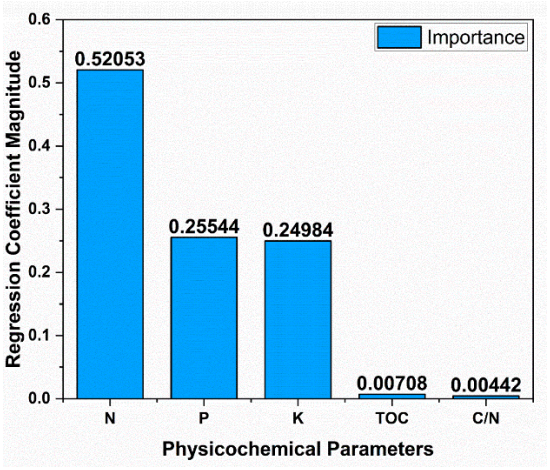

Figure 12. Relative regression coefficients of the physicochemical parameters included in the multiple linear regression analysis of FI.

3.8. Principal Component Analysis

PCA was performed to identify patterns and relationships in the multivariate dataset. Figure 13 presents a PCA biplot displaying the distribution of compost samples relative to first two principal components and the corresponding loading vectors for each measured variable. The results indicate that the variables associated with nutrients group together, indicating their common influence on the fertilizing capacity of compost. In contrast, heavy metal variables are scattered across different directions, suggesting multiple independent sources during the composting operation. The dispersion of variables and samples in the PCA plot reveals that the complexity of compost quality and confirms that value of employing multivariate analytical techniques in determining key factors that influence compost properties.

PCA revealed that the first two principal components explained a major proportion of the total variance in compost characteristics. The loading values of the first two principal components are presented in Table S5 presents PCA eigenvalues and loading coefficients. PC1 was strongly associated with nutrient parameters (TOC, N, P, and K) and FI, whereas PC2 was mainly influenced by heavy metals such as Zn, Cu, and Pb. The distribution of samples in the PCA plot indicates variation in compost quality among different composting treatments. This indicates that nutrient variability dominates compost quality, while heavy metals contribute secondary variability

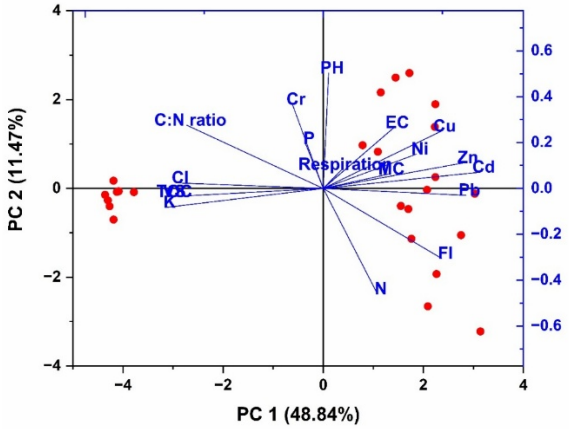

Figure 13. PCA biplot showing the relationships among physicochemical parameters, nutrients, heavy metals, and compost maturity indices (FI and CI) for compost samples (n = 25).

3.9. Compost Quality Classification

Based on the combined evaluation of FI and CI values, the compost samples were classified into quality categories [32,38,39] as illustrated in Figure 14. The classification scheme integrates nutrient-related fertility characteristics and selected heavy-metal concentrations to provide an overall quality classification. The results showed that 24 samples were classified as Class C, while one sample was classified as Class D, indicating variation in the combined FI-CI quality characteristics among the samples.

The FI-CI classification provides a useful screening-level assessment of compost quality based on the measured nutrient and heavy-metal parameters. However, classification based on FI and CI alone does not establish direct agronomic suitability. In particular, plant growth response, seed germination, phytotoxicity, pathogen safety, and field performance were not evaluated in the present study. Therefore, the Class C designation should be interpreted as indicating favourable quality characteristics within the FI-CI framework rather than as definitive evidence of suitability for food-crop or general agricultural application. Further germination, phytotoxicity, microbiological safety, and field-validation studies would be required to establish agronomic suitability.

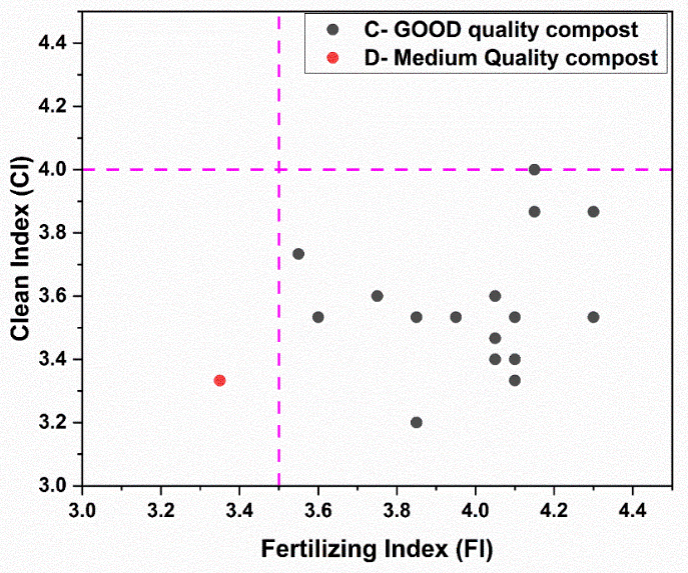

Figure 14. Classification of compost samples into quality classes based on Fertilizer Index (FI) and Clean Index (CI).

4. Conclusions

This study evaluated 25 composite samples of finished windrow compost from a centralized MSW processing facility in Hyderabad using physicochemical characterization, selected heavy-metal analysis, FI–CI classification, and multivariate statistical methods. The samples had a mean pH of 7.39 ± 0.18, EC of 4.33 ± 0.44 dS m^{-1}, and C/N ratio of 14.44 ± 4.19. The measured concentrations of Zn, Cu, Cd, Pb, Ni, and Cr were below the respective limits reported in Table 2 when assessed using the reported mean values. FI ranged from 3.35 to 4.30 and CI from 3.20 to 4.00; the applied FI–CI scheme classified 24 samples as Class C and one as Class D. Pearson correlation and PCA were used to explore associations and patterns among the measured variables. The regression analysis describes the statistical association between FI and the variables used in its calculation and should not be regarded as independent predictive validation. Because Hg and As were not analysed and no germination, phytotoxicity, pathogen, plant-growth, or field trials were performed, the results do not establish complete biological safety or crop-specific suitability. Overall, the findings provide a facility-specific assessment of the measured physicochemical and selected-metal parameters and indicate the need for broader seasonal monitoring and biological validation before agricultural-use.

5. Practical Implications

This study demonstrates the usefulness of combining FI and CI with multivariate analysis to summarize measured nutrient-related properties and selected-metal concentrations in finished compost from a centralized urban facility. The interpretation is subject to several limitations. The investigation relied on 25 composite samples from a single windrow facility, and exact sampling dates, collection intervals, and multi-seasonal coverage were not documented. Hg and As were not analysed. In addition, seed germination, phytotoxicity, pathogen, crop-

growth, and field-validation tests were outside the scope of this study. Continuous operational data, including daily windrow-core temperature profiles and quantitative oxygen-flow measurements, were not available. The respiration-rate unit and test protocol also require clarification. Future work should include seasonally distributed sampling across multiple facilities, a broader contaminant suite, standardized stability and phytotoxicity tests, pathogen assessment, and crop/field trials. Until such validation is available, FI–CI classes should be interpreted as an index-based screening classification and not as stand-alone evidence of agricultural safety or crop suitability.

Supplementary Materials

The additional data and information can be downloaded at: https://media.sciltp.com/articles/others/26111 11335014134/BCCN-26090081-Supplementary-Materials.pdf. Table S1: Complete dataset of physicochemical properties, nutrients, and heavy metals (n = 25). Table S2: Fertilizing Index (FI) calculation details. Table S3: Clean Index (CI) calculation details based on heavy metal concentrations. Table S4: Multiple linear regression results for prediction of fertilizing index. Table S5: Principal Component Analysis (PCA) eigenvalues and variance. Table S6: Classification of Compost Based on Fertilizing Index and Clean Index: Classification of MSW compost for their marketability and uses.

Author Contributions

V.G.: conceptualization, methodology, software, L.N.R.: data curation, writing—original draft preparation, writing—reviewing and editing, B.N.T.: supervision, writing—reviewing and editing, B.G.: writing—reviewing and editing, K.M.G.: validation, writing—reviewing and editing and M.K.J.: visualization, investigation, validation, writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

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Not applicable.

Data Availability Statement

All data generated or analysed during this study are included in this published article and its Supplementary Material.

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Conflicts of Interest

The authors declare no conflict of interest

Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used ChatGPT 5.6 to assist with the graphical abstract figure generation, paraphrasing and language editing. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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