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Process-Level Noise and Vibration Hazard Characterization for Engineering Control Prioritization in a Bottled Water Manufacturing Facility

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Abstract

Machine-generated noise and vibration vary considerably across manufacturing processes, yet engineering interventions are frequently implemented without quantitative process-level prioritization. This study characterized workstation vibroacoustic conditions in a semi-automated bottled water manufacturing facility to identify production units requiring priority engineering control. Field measurements of machine generated noise and mechanical vibration were carried out using calibrated sound level and vibration meters, in the polyethylene terephthalate (PET) Blow, Water Treatment and Bottling/Packaging sections during ambient, idle and production operating conditions. Descriptive statistics, coefficients of variation, one-way analysis of variance (ANOVA), Games–Howell post hoc comparisons, and an Engineering Control Priority Index (ECPI) were applied to determine differences between production units and to rank intervention priorities. During production, the Water Treatment and Bottling/Packaging sections had higher mean noise levels (92.83 and 92.32 dB(A)) and vibration accelerations (7.15 and 7.29 m/s²) than the PET Blow section. Significant differences were found for both noise ($p < 0.001$, $\eta^2 = 0.723$) and vibration ($p < 0.001$, $\eta^2 = 0.765$). ECPI analysis identified the Water Treatment and Bottling/Packaging sections as the highest priorities for engineering intervention. The proposed framework provides a practical basis for engineering control prioritization and maintenance planning in manufacturing environments.

Keywords: *Engineering control prioritization; Industrial hygiene; Mechanical vibration; Noise; Process-level hazard characterization; Vibroacoustic assessment.*

1. Introduction

Machine-generated noise and mechanical vibration are two of the most common physical hazards in industrial environments. This is especially true for manufacturing systems that involve the continuous operation of rotating, reciprocating and impact-producing equipment. Vibroacoustic emissions are generated by production processes such as pumping, conveying, blow moulding, filling, packaging and handling of materials and create complex work place environments with hazard levels differing significantly between production units. Although the technological development in the manufacturing process has been improved, the exposure of noise and vibration from industries still remains as one of the most common issues in the manufacturing industry [1 – 3]. In addition to their well-known links to hearing loss, musculoskeletal disorders, vascular dysfunction and reduced operational performance, uncontrolled vibroacoustic emissions can also be an indication of inefficient machine operation, poor maintenance, structural deterioration or improper equipment installation. Thus, noise and vibration should be considered as a health hazard as well as an engineering indicator of machine performance and production system integrity.

The hierarchy of controls forms the basis for effective industrial noise and vibration management and is an order of controls that begins with elimination and engineering controls, followed by administrative controls and personal protective equipment. However, to implement engineering controls, one needs a detailed understanding of where machine-generated emissions are coming from, how they vary from production process to production process, and which equipment is the greatest contributor to the overall vibroacoustic environment. Recent investigations have emphasized the value of process-level hazard characterization, spatial hazard mapping, and workstation-specific assessments for identifying dominant sources of industrial noise and vibration and

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guiding evidence-based engineering interventions [4 – 6]. Rather than treating manufacturing facilities as acoustically homogeneous environments, these approaches recognize that individual production processes exhibit distinct operational characteristics that require process-specific engineering solutions.

Most published investigations have focused primarily on occupational exposure assessment by estimating worker noise doses, evaluating vibration exposure, or examining associated health outcomes. Although these studies provide valuable information regarding occupational risk, they often provide limited insight into the engineering characteristics of the production processes responsible for generating noise and vibration. Consequently, opportunities to prioritize engineering interventions at the machine or process level may remain underutilized. Recent reviews have similarly highlighted that, despite extensive documentation of industrial noise and vibration hazards, comparatively fewer studies have integrated field measurements with analytical approaches capable of distinguishing process-specific emission characteristics and supporting engineering decision-making [2, 7]. This limitation is particularly evident in manufacturing facilities where multiple production units operate simultaneously but differ considerably in machine configuration, operating principles, and mechanical loading conditions.

The manufacturing industry, particularly food and beverage production, provides an important context for process-level vibroacoustic characterization because production lines typically combine compressors, pumps, conveyor systems, blow molding machines, filling equipment, capping units, and packaging systems operating under different mechanical conditions. These systems generate diverse acoustic and vibration signatures that vary according to machine type, production stage, operating load, and maintenance condition. Recent investigations in manufacturing environments have reported substantial differences in machine-generated noise between production processes, reinforcing the need for workstation-specific assessments rather than generalized facility-level evaluations [1]. Understanding these process-dependent variations is essential for optimizing maintenance strategies, prioritizing engineering controls, and improving the efficiency of industrial noise and vibration management programs.

These challenges are particularly relevant in developing countries, where rapid industrialization is frequently accompanied by limited occupational hygiene infrastructure, constrained maintenance resources, and inconsistent implementation of engineering controls. Nigeria represents one of the fastest-growing manufacturing economies in Sub-Saharan Africa, with the packaged drinking water industry expanding rapidly in response to increasing urbanization and persistent limitations in public water supply. Modern bottled water production facilities integrate several mechanized processes, including polyethylene terephthalate (PET) blow molding, water treatment, bottle filling, capping, labeling, and packaging. While these operations are essential for efficient production, they also constitute potential sources of sustained machine-generated noise and vibration. Despite the continued growth of this sector, published engineering studies describing the spatial distribution and process-specific characteristics of vibroacoustic conditions within bottled water manufacturing facilities remain scarce, particularly in Nigeria and the wider West African region. Existing Nigerian studies have largely concentrated on occupational noise in sawmills, palm oil mills, and other processing industries, leaving bottled water production comparatively underrepresented in the literature.

Another limitation of existing studies is the predominant reliance on descriptive summaries without comprehensive inferential evaluation of differences among production processes. Statistical approaches such as analysis of variance, effect size estimation, and multiple comparison procedures provide objective evidence for determining whether observed differences among production units represent genuine process-related variation rather than random operational fluctuations. When integrated with descriptive measures of variability, these analytical methods provide a stronger basis for identifying priority engineering targets and allocating resources for machine improvement and maintenance. Furthermore, existing studies rarely integrate process-level measurements with structured engineering prioritization frameworks capable of supporting evidence-based intervention planning. Consequently, there remains a need for analytical approaches that combine field measurements, inferential statistical analysis, and engineering prioritization metrics to support industrial decision-making.

Accordingly, this study presents a field-based characterization of workstation-level noise and mechanical vibration across the principal production units of a semi-automated bottled water manufacturing facility in Nigeria. Measurements were obtained under ambient, idle, and normal production conditions to characterize the magnitude, variability, and operational behaviour of machine-generated vibroacoustic emissions. Descriptive statistics, confidence intervals, coefficients of variation, one-way analysis of variance, effect size estimation, Games–Howell multiple comparisons, and an Engineering Control Priority Index (ECPI) were employed to evaluate differences among production units and identify statistically distinct operational profiles. Rather than estimating individual worker exposure or determining regulatory compliance, the study adopts a process-level engineering perspective to support hazard characterization and engineering control prioritization. The findings provide quantitative evidence for identifying production units requiring priority engineering intervention while establishing a practical analytical framework that may be applied to similar manufacturing environments where process-specific management of machine-generated noise and vibration is required.

2. Materials and Methods

2.1. Study Design and Study Site

A field-based industrial hygiene survey was conducted in a semi-automated bottled water manufacturing facility in Nigeria to characterize process-level machine-generated noise and mechanical vibration across major production units. The investigation adopted an engineering perspective aimed at identifying production units exhibiting elevated and persistent vibroacoustic conditions requiring priority intervention rather than estimating individual worker exposure.

The production line consisted of three principal operational units: the polyethylene terephthalate (PET) blow molding section, the water treatment section, and the bottling and packaging section. These units contain the facility's major mechanical equipment and represent the dominant sources of machine-generated noise and vibration associated with bottle production, water purification, filling, capping, conveying, and packaging operations.

2.2. Instrumentation

Mechanical vibration measurements were obtained using a handheld digital vibrometer (VM-6360, Guangzhou Landtek Instruments Co., Ltd., China) capable of measuring acceleration, velocity, and displacement over a frequency range of 10 Hz–1 kHz. Vibration acceleration (m/s^2) was selected as the principal parameter because it is highly sensitive to machine operating conditions and facilitates comparison of vibration intensity among production units.

Noise measurements were obtained using a portable Type 2 sound level meter operating with A-weighting and Fast response settings over a measurement range of 30–130 dB(A) (insert manufacturer and model number). Equivalent continuous sound pressure levels (Leq) were measured at representative workstation locations. Instrument functionality checks were performed before and after each measurement session to ensure measurement consistency.

2.3. Measurement Procedure

Measurements were conducted during normal production shifts under three operating conditions:

- ambient condition, with all production equipment switched off;
- idle condition, with equipment energized but not processing materials; and
- production condition, with equipment operating under routine manufacturing loads.

Noise measurements were collected approximately 1.5 m above floor level and at least 1 m from major reflective surfaces to represent operator workstation conditions, following principles derived from workplace noise assessment standards such as ISO 9612 and ISO 1996. Vibration measurements were recorded directly from machine casings, support structures, and equipment frames using firm probe contact in general accordance with machine vibration assessment principles outlined in ISO 20816-1.

Each measurement was recorded continuously for 60 s. Twenty repeated measurements were obtained for each production unit under each operating condition, yielding 180 observations in total. Sampling was distributed across multiple production cycles to capture operational variability and provide sufficient observations for inferential statistical analysis.

2.4. Hazard Characterization Framework

The investigation adopted a process-level hazard characterization approach rather than personal exposure assessment. Accordingly, measured noise and vibration values were interpreted as indicators of workstation environmental conditions and machine operating characteristics rather than estimates of worker exposure. Personal noise dose, time-weighted average (TWA), daily vibration exposure normalization [A(8)], hand-arm vibration exposure, and whole-body vibration exposure indices were therefore not evaluated.

2.5. Data Analysis

Data were analysed using descriptive and inferential statistics. Mean, minimum, maximum, standard deviation, 95% confidence interval, and coefficient of variation were calculated for each production unit and operating condition. The coefficient of variation was used to quantify operational stability and temporal variability.

Differences among production units were evaluated using one-way analysis of variance (ANOVA). Data normality and homogeneity of variance were assessed using the Shapiro-Wilk and Levene tests, respectively. Where variance heterogeneity was identified, Games–Howell post hoc comparisons were performed. Effect sizes were quantified using eta squared (η^2), and statistical significance was established at $p < 0.05$. Statistical analyses were conducted using the Statistical Package for the Social Sciences (SPSS) version 27.0.

2.6. Engineering Control Priority Index

An Engineering Control Priority Index (ECPI) was developed to rank production units according to noise level, vibration intensity, and operational stability. Four parameters were considered: mean production noise level, mean production vibration acceleration, coefficient of variation of production noise, and coefficient of variation of production vibration.

Each parameter was normalized using min–max normalization:

$$X_{norm} = \frac{X - X_{min}}{X_{max} - X_{min}}$$

Because sustained and stable emissions provide greater opportunities for source-oriented engineering interventions than highly intermittent emissions, operational stability was represented using the inverse of the normalized coefficients of variation:

$$ECPI = 0.25\,N + 0.25\,V + 0.25\,(1 - CV_N) + 0.25\,(1 - CV_V)$$

where N and V represent normalized production noise and vibration levels, while CV_N and CV_V represent normalized coefficients of variation for noise and vibration, respectively.

Equal weighting coefficients were assigned to all components to avoid introducing subjective bias because no empirical, regulatory, or industrial evidence was available to justify differential weighting among the contributing parameters.

Production units with larger ECPI values were considered higher priorities for engineering intervention because they combined elevated vibroacoustic magnitudes with sustained operational stability.

2.7. Ethical Considerations

The investigation involved environmental measurements only and did not include human participants, biological sampling, or medical examinations. Permission to conduct the study was obtained from facility management, and all measurements were performed without disrupting routine production activities.

3. Results and Discussion

3.1. Baseline Vibroacoustic Characterization

Baseline measurements were obtained prior to equipment operation to establish the ambient vibroacoustic environment of the manufacturing facility and provide a reference for evaluating machine-generated emissions during idle and production conditions. Ambient vibration remained low, ranging from 0.10 to 0.30 m/s² with a mean value of 0.18 ± 0.05 m/s², while ambient sound pressure levels ranged from 41.00 to 42.00 dB(A), yielding a mean value of 41.30 ± 0.35 dB(A) (Table 1). The narrow measurement ranges, together with the very low coefficient of variation for noise (0.85%) and moderate variability for vibration (27.78%), indicate minimal environmental disturbance during data collection. Establishing baseline conditions enables machine-generated emissions to be distinguished from background environmental influences and improves the reliability of process-level hazard characterization. Similar approaches have been adopted in manufacturing environments where multi-sensor monitoring systems demonstrated the importance of stable baseline conditions for accurate workplace hazard assessment [8]. The low ambient noise and vibration levels observed in this study therefore confirm that the increases recorded during idle and production operations were primarily attributable to manufacturing equipment rather than external environmental sources. Furthermore, because the baseline ambient noise level of 41.30 dB(A) was substantially lower than the operational noise levels observed during production, background noise correction was considered unnecessary for comparative process-level evaluation.

3.2. Descriptive Statistical Characterization of Vibroacoustic Conditions

Descriptive statistics were used to characterize workstation noise and machine vibration under idle and production operating conditions across the PET Blow, Water Treatment, and Bottling/Packaging sections. Mean values, confidence intervals, and coefficients of variation were used to evaluate emission magnitude and operational stability, with the results presented in Tables 2 and 3.

3.2.1. Idle Operating State

During idle operation, measurable differences were observed among production units (Table 2). The PET Blow section exhibited the highest mean vibration acceleration (3.73 ± 1.48 m/s²) and the greatest variability (CV = 39.68%), whereas lower variability was observed in the Water Treatment (23.55%) and Bottling/Packaging (19.64%) sections. Idle-state noise levels ranged from 68.87 ± 6.55 dB(A) in the Water Treatment section to 73.60 ± 4.29 dB(A) in the Bottling/Packaging section.

The elevated variability observed in the PET Blow section is consistent with the intermittent operation of blow-moulding equipment involving cyclic pneumatic actuation and mould movement, whereas the Water Treatment and Bottling/Packaging sections are dominated by continuously operating pumps, conveyors, and rotating machinery exhibiting more stable behaviour [9].

Table 1. Baseline Ambient Noise and Vibration Conditions Prior to Equipment Operation

Variable	Mean ± SD	Minimum	Maximum	95% CI	CV (%)
Ambient Noise (dB(A))	41.30 ± 0.35	41.00	42.00	[41.14, 41.46]	0.85
Ambient Vibration (m/s²)	0.18 ± 0.05	0.10	0.30	[0.16, 0.20]	27.78

Table 2. Descriptive Statistics of Noise and Vibration During Idle Operation

Production Unit	Noise Mean ± SD (dB(A))	Noise 95% CI	Noise CV (%)	Vibration Mean ± SD (m/s²)	Vibration 95% CI	Vibration CV (%)
PET Blow	71.38 ± 3.39	[69.79, 72.97]	4.75	3.73 ± 1.48	[3.04, 4.42]	39.68
Water Treatment	68.87 ± 6.55	[65.80, 71.94]	9.51	3.27 ± 0.77	[2.91, 3.63]	23.55
Bottling/Packaging	73.60 ± 4.29	[71.59, 75.61]	5.83	2.75 ± 0.54	[2.50, 3.00]	19.64

3.2.2. Production Operating State

During production, substantial increases in both noise and vibration were observed across all production units (Table 3). Mean vibration acceleration increased to 7.15 ± 0.69 m/s² and 7.29 ± 0.68 m/s² in the Water Treatment and Bottling/Packaging sections, respectively, whereas the PET Blow section recorded a lower mean value of 3.95 ± 1.25 m/s².

Similarly, mean production noise levels reached 92.83 ± 0.81 dB(A) in the Water Treatment section and 92.32 ± 1.25 dB(A) in the Bottling/Packaging section, substantially exceeding the PET Blow section (79.60 ± 6.13 dB(A)). Noise variability remained below 2% in the Water Treatment and Bottling/Packaging sections, while vibration variability also decreased to below 10%, indicating stable machine operation during production. In contrast, the PET Blow section maintained substantially greater variability (31.65%), reflecting the intermittent loading associated with blow-moulding operations.

The production noise levels recorded in the Water Treatment and Bottling/Packaging sections exceeded the commonly adopted occupational action level of 85 dB(A), further supporting the need for engineering control prioritization within these production units. These observations agree with previous findings that continuously operating industrial equipment generates more stable vibroacoustic emissions than cyclic machinery operating under intermittent loading conditions [10, 11].

3.3. Inferential Statistical Analysis

Inferential statistical analyses were performed to determine whether the observed differences in production noise and vibration among the PET Blow, Water Treatment, and Bottling/Packaging sections represented statistically significant process-level variations rather than random measurement variability. One-way analysis of variance (ANOVA) was used to compare mean production noise and vibration levels across production units, while Games–Howell post hoc comparisons were subsequently performed because variance homogeneity assumptions were not satisfied.

3.3.1. Comparative Analysis of Production Noise

The ANOVA results for production noise are presented in Table 4. A highly significant difference in production noise was observed among the three production units ($F(2,57) = 74.28$, $p < 0.001$). The corresponding effect size ($\eta^2 = 0.723$) indicates that approximately 72.3% of the total variation in workplace noise was attributable to differences among production units, representing a large practical effect.

The large effect size suggests that machine configuration and production process were the dominant determinants of the workplace acoustic environment rather than random operational variability. Similar process-dependent differences in machine-generated noise have been reported in industrial manufacturing systems operating under different mechanical configurations [9, 12]. The findings therefore support process-specific prioritization of engineering noise-control measures within the facility.

Table 3. Descriptive Statistics of Noise and Vibration During Production Operation

Production Unit	Noise Mean ± SD (dB(A))	Noise 95% CI	Noise CV (%)	Vibration Mean ± SD (m/s²)	Vibration 95% CI	Vibration CV (%)
PET Blow	79.60 ± 6.13	[76.73, 82.47]	7.70	3.95 ± 1.25	[3.36, 4.54]	31.65
Water Treatment	92.83 ± 0.81	[92.45, 93.21]	0.87	7.15 ± 0.69	[6.83, 7.47]	9.65
Bottling/Packaging	92.32 ± 1.25	[91.73, 92.91]	1.35	7.29 ± 0.68	[6.97, 7.61]	9.33

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Table 4. One-Way ANOVA for Production Noise Levels Across Production Units

Source of Variation	Sum of Squares (SS)	df	Mean Square (MS)	F	p-value	η²
Between Groups	2279.74	2	1139.87	74.28	<0.001	0.723
Within Groups	874.77	57	15.35			
Total	3154.51	59				

Table 5. One-Way ANOVA for Production Vibration Levels Across Production Units

Source of Variation	Sum of Squares (SS)	df	Mean Square (MS)	F	p-value	η²
Between Groups	147.25	2	73.63	92.73	<0.001	0.765
Within Groups	45.26	57	0.79			
Total	192.51	59				

3.3.2. Comparative Analysis of Production Vibration

The ANOVA results for production vibration are presented in Table 5. Significant differences were observed among the three production units ($F(2,57) = 92.73$, $p < 0.001$). The effect size ($\eta^2 = 0.765$) indicates that approximately 76.5% of the variation in vibration acceleration was explained by production unit differences, representing an even larger effect than that observed for noise.

The stronger effect size for vibration suggests that machine-specific structural dynamics and vibration transmission characteristics contributed more strongly to process differences than airborne noise alone. Similar observations have been reported in industrial vibration investigations where machinery design and loading characteristics were identified as major determinants of vibration behavior [10, 11]. These findings further support the need for production-specific engineering interventions.

3.3.3. Games–Howell Post Hoc Comparisons

Games–Howell post hoc comparisons were performed to identify the production units responsible for the observed differences (Table 6). The PET Blow section differed significantly from both the Water Treatment and Bottling/Packaging sections for production noise and vibration (adjusted $p < 0.001$ for all comparisons). In contrast, no significant differences were observed between the Water Treatment and Bottling/Packaging sections for either noise ($p = 0.385$) or vibration ($p = 0.742$).

These findings indicate the presence of two statistically distinct vibroacoustic operational groups within the facility: an intermittent process represented by the PET Blow section and a continuous-process group represented by the Water Treatment and Bottling/Packaging sections. Similar clustering of vibroacoustic behavior according to machinery operating mode has been reported in previous manufacturing studies [9, 10].

From an engineering perspective, the comparable vibroacoustic characteristics of the Water Treatment and Bottling/Packaging sections suggest that similar control strategies may be applicable to both units, whereas the PET Blow section requires process-specific interventions targeting transient mechanical impacts associated with cyclic machine operation.

Table 6. Games–Howell Post Hoc Comparisons of Production Noise and Vibration

Variable	Comparison	Mean Difference	95% CI	Adjusted p-value	Decision
Noise (dB(A))	PET Blow vs Water Treatment	-13.23	[-16.59, -9.87]	<0.001	Significant
	PET Blow vs Bottling/Packaging	-12.72	[-16.13, -9.31]	<0.001	Significant
	Water Treatment vs Bottling/Packaging	0.51	[-0.29, 1.31]	0.385	Not Significant
Vibration (m/s^2)	PET Blow vs Water Treatment	-3.20	[-3.98, -2.42]	<0.001	Significant
	PET Blow vs Bottling/Packaging	-3.34	[-4.12, -2.56]	<0.001	Significant
	Water Treatment vs Bottling/Packaging	-0.14	[-0.65, 0.37]	0.742	Not Significant

3.4. Process-Level Hazard Characterization

The descriptive and inferential analyses demonstrated that vibroacoustic emissions within the bottled water manufacturing facility were strongly process-dependent rather than uniformly distributed across production units. The large ANOVA effect sizes indicated that production unit accounted for 72.3% of the variation in workplace noise and 76.5% of the variation in vibration acceleration, confirming that machine configuration and operating characteristics were the principal determinants of the observed emissions.

Games–Howell comparisons further identified two distinct operational groups within the facility. The Water Treatment and Bottling/Packaging sections exhibited statistically comparable noise and vibration characteristics, whereas both differed significantly from the PET Blow section. The similarity between the Water Treatment and Bottling/Packaging units is consistent with the presence of continuously operating pumps, motors, conveyors, filling systems, and other rotating machinery that generate relatively stable steady-state forced vibration and sustained vibroacoustic emissions.

In contrast, the PET Blow section exhibited lower average noise and vibration levels but substantially greater variability, reflecting the cyclic nature of blow-moulding operations involving mould closure, compressed-air expansion, pressure release, and product ejection. Consequently, the PET Blow section represents an intermittent vibroacoustic environment characterized by transient mechanical events rather than continuous machine emissions.

These findings demonstrate the importance of considering operational variability alongside average emission magnitude during industrial hazard characterization. While mean values quantify emission intensity, variability measures provide additional information regarding process stability and machine operating behaviour. The combined consideration of both parameters therefore provides a more comprehensive basis for engineering decision-making than average values alone.

The Engineering Control Priority Index supported this interpretation by integrating noise level, vibration intensity, and operational stability into a single decision-support metric. The Water Treatment and Bottling/Packaging sections achieved the highest priority scores because they combined elevated vibroacoustic magnitudes with sustained operational stability, characteristics that favour source-oriented engineering interventions. Conversely, the PET Blow section exhibited lower priority scores despite its greater variability, indicating that mitigation efforts should focus primarily on transient impacts and cyclic disturbances rather than large-scale structural modifications.

The distinction between continuous and intermittent operational profiles has important implications for maintenance and hazard control strategies. Previous studies have shown that continuously operating rotating equipment often generates persistent vibration patterns influenced by machine balance, alignment, and loading conditions, whereas intermittent pneumatic systems exhibit greater temporal variability [13 – 14]. Similarly, abnormal vibration behavior frequently precedes equipment failure, highlighting the importance of vibration monitoring in predictive maintenance, condition-based maintenance, and asset condition management programs [15 – 16].

Overall, the findings establish a quantitative basis for process-specific hazard characterization and engineering control prioritization within bottled water manufacturing facilities. Continuous-process units are likely to benefit most from source-oriented engineering controls, whereas intermittent systems require mitigation strategies targeted at transient mechanical events and cyclic machine operations.

3.5. Engineering Control Prioritization

The Engineering Control Priority Index (ECPI) was developed to support evidence-based prioritization of engineering interventions according to the magnitude and stability of measured vibroacoustic emissions. The resulting rankings are presented in Table 8.

Table 8. Engineering Control Priority Index (ECPI) Ranking of Production Units

Production Unit	Normalized Noise (N)	Normalized Vibration (V)	1 − CVN	1 − CVV	Final ECPI Score	Priority Rank
Water Treatment	1.0000	0.9581	1.0000	0.9857	0.9860	1
Bottling/Packaging	0.9615	1.0000	0.9297	1.0000	0.9728	2
PET Blow	0.0000	0.0000	0.0000	0.0000	0.0000	3

The ECPI analysis identified the Water Treatment (ECPI = 0.9860) and Bottling/Packaging (ECPI = 0.9728) sections as the highest-priority engineering targets because they combined elevated noise and vibration levels with sustained operational stability. Their statistical similarity observed in the Games–Howell analysis further suggests that comparable engineering intervention strategies may be effective across both production units.

For these continuous-process systems, engineering controls should primarily emphasize source-oriented and path-control measures. Appropriate interventions include vibration isolation systems and resilient machine mounts for vibration transmission control, together with dynamic balancing of rotating components, improved shaft alignment, preventive maintenance of bearings and drive systems, and acoustic enclosure of major noise sources. Previous studies have demonstrated that such interventions provide effective and sustainable reductions in workplace vibroacoustic exposure [17 – 19].

In contrast, the PET Blow section exhibited substantially greater operational variability despite lower average vibroacoustic magnitudes (ECPI = 0.0000). Consequently, engineering improvements within this production unit should focus on mitigating transient mechanical events associated with mould closure, compressed-air expansion, and product ejection rather than implementing broad structural modifications. Potential interventions include optimization of pneumatic operating sequences, localized damping treatments, and targeted acoustic control around repetitive impact sources.

Overall, the ECPI framework demonstrates that engineering resources should be directed preferentially toward production units exhibiting both elevated vibroacoustic magnitudes and sustained operating conditions. This approach supports efficient allocation of maintenance resources and aligns with the hierarchy of controls by emphasizing source-level engineering interventions before administrative controls and personal protective equipment [7, 20 – 21].

3.6. Engineering Implications

The present investigation demonstrates the value of integrating process-level hazard characterization with inferential statistical analysis to support engineering decision-making in industrial environments. The combined use of descriptive statistics, ANOVA, Games–Howell comparisons, effect sizes, and the Engineering Control Priority Index (ECPI) provided an objective framework for distinguishing systematic process-related differences from random operational variability and for prioritizing engineering interventions accordingly.

The statistical analyses identified the Water Treatment and Bottling/Packaging sections as the dominant sources of sustained machine-generated noise and vibration within the facility. Their high ECPI scores and stable operating characteristics indicate that source-oriented engineering controls, including vibration isolation, machine balancing, acoustic enclosures, and preventive maintenance, are likely to provide the greatest reduction in workplace vibroacoustic exposure.

In contrast, the PET Blow section exhibited lower average emissions but substantially greater temporal variability associated with cyclic machine operation. Engineering interventions within this production unit should therefore focus on mitigating transient mechanical events associated with mold closure, compressed-air expansion, and product ejection rather than implementing broad structural modifications.

The findings also highlight the close relationship between vibroacoustic behavior and equipment condition monitoring. Establishing baseline noise and vibration signatures for individual production units may support predictive maintenance and vibroacoustic signature analysis by enabling abnormal operating conditions and emerging machine faults to be identified before major equipment failures occur [15].

Overall, the analytical framework developed in this study provides an evidence-based approach for allocating engineering resources according to statistically supported process priorities rather than uniform facility-wide interventions. Although developed for bottled water manufacturing, the methodology may also be applicable to other manufacturing sectors involving multiple production units operating under different mechanical conditions.

4. Conclusions

This study characterized workstation vibroacoustic conditions within a semi-automated bottled water manufacturing facility using field measurements of machine-generated noise and vibration under ambient, idle, and production operating conditions. The investigation emphasized comparative evaluation of production processes to support engineering control prioritization rather than worker exposure assessment.

Descriptive analysis revealed clear differences in vibroacoustic magnitude and operational stability among production units. The Water Treatment and Bottling/Packaging sections exhibited higher mean noise and vibration levels together with lower variability, indicating sustained and stable machine-generated emissions. In contrast, the PET Blow section demonstrated lower average vibroacoustic levels but greater temporal variability associated with intermittent blow-moulding operations.

Inferential statistical analysis confirmed that these differences were statistically significant. One-way ANOVA identified significant differences among production units for both production noise ($F(2,57) = 74.28$, $p < 0.001$, $\eta^2 = 0.723$) and production vibration ($F(2,57) = 92.73$, $p < 0.001$, $\eta^2 = 0.765$). Games–Howell comparisons further demonstrated that the Water Treatment and Bottling/Packaging sections exhibited statistically comparable vibroacoustic characteristics, whereas both differed significantly from the PET Blow section.

The Engineering Control Priority Index identified the Water Treatment and Bottling/Packaging sections as the highest priorities for engineering intervention because of their elevated and stable machine-generated emissions, while the PET Blow section required mitigation strategies directed toward transient mechanical events associated with cyclic operation.

The findings demonstrate that integrating repeated field measurements with comparative statistical analysis and engineering prioritization metrics provides an objective basis for cost-effective, process-specific noise and vibration management within manufacturing environments. The proposed framework may also support maintenance planning and engineering resource allocation in facilities containing multiple production units with differing operating characteristics.

The findings are based on measurements obtained from a single manufacturing facility and should therefore be interpreted within that context. Future investigations involving multiple facilities, alternative production technologies, and continuous real-time monitoring systems would improve the generalizability of the proposed methodology and further strengthen its application to industrial vibroacoustic management.

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