Jurnal Teknik Industri, Vol. 28, No. 2, December 2026
ISSN 1411-2485 print / ISSN 2087-7439 online
DOI: 10.9744/jti.28.2.139-151

An Ergo–Green–Lean Framework for Sustainability Performance Assessment in Coffee Agroindustry

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Abstract: There is growing pressure in the manufacturing sector to address operational efficiency alongside environmental and worker well-being. However, major existing sustainability assessment methods have notable flaws: most evaluate ergonomic, environmental, and operational performance separately. This approach cannot identify cross-dimensional performance gaps, nor can it support integrated operational decision-making. To address this issue, this study proposes an integrated Ergonomic-Green-Lean (EGL) manufacturing performance assessment framework for the coffee agroindustry. The method uses the Fuzzy Analytical Hierarchy Process (Fuzzy AHP) to determine indicator weights under uncertain expert judgment, and a Traffic Light System (TLS) for performance level classification. The calculated weights for the three dimensions are 0.36 for ergonomics, 0.34 for lean practices, and 0.30 for green practices. However, ergonomics made the lowest actual contribution to performance. The overall EGL performance index reached 67.7%, which falls in the medium range. The core finding is that there is a clear mismatch between the strategic importance of human factors in this production system and their actual performance. The proposed EGL framework links indicator importance with realized operational performance, enabling the identification of importance–performance mismatches and supporting more coordinated improvement priorities.

Keywords: Ergo–Green–Lean; Fuzzy AHP; Manufacturing Performance; Sustainability Assessment; Coffee Processing.

Introduction

Manufacturing has an important role in economic development and technological development yet the way manufacturing performance is evaluated has changed substantially. Production systems are no longer measured solely in productivity and output and cost efficiency but also in their capacity to protect human well-being, reduce environmental impact and operate efficiently. This change is due to stricter regulations, growing concern over climate change and more attention to human rights and decent working conditions [1, 2]. Hence, production system performance needs to be measured by more than output and cost [3]. Environmental performance and work conditions are also essential for the assessment of production system performance at the shopfloor or factory level and are directly involved in the interactions of processes, resources, machines and human factors [4]. In labor-intensive operations, excessive manual activities such as material handling and packaging can increase ergonomic risks and lead to physical and mental fatigue [5]. Moreover, poor lean implementation can lead to operational waste, namely lead time and non-value-added activities [6], and environmental concerns may not be considered due to high energy consumption and inefficient waste disposal [7]. These situations indicate that shopfloor performance problems are multi-dimensional and interrelated. As such, an operational-level analysis of human, environmental and process efficiency factors should be applied to a single manufacturing performance framework.

There are several studies that have examined different aspects of manufacturing system performance, but many remain fragmented or focus on selected dimensions. The Triple Bottom Line (TBL) has been used for industrial sustainability analysis from economic, environmental and social perspectives [8, 9]. But TBL is mostly a strategic approach, and it is not always translated into operational insights on the shop floor [10, 11]. Previous studies have also integrated lean–green, lean–ergonomics, and sustainable manufacturing approaches [12-15]. However, these approaches do not always explicitly link indicator importance with actual operational performance or adequately reveal performance imbalances among worker well-being, environmental performance, and process efficiency. Although previous studies suggest that these dimensions may influence one another in operational settings, existing assessment approaches do not necessarily quantify these interactions or reveal whether strategically important dimensions remain underperforming. At the methodological level, indicator weighting and expert consensus are widely employed in indicator-based sustainability assessment because it is a well-defined and well-structured method to decide [16, 17]. However, crisp-value-based approaches do not adequately capture the uncertainty inherent in human judgment [18]. Furthermore, many assessment approaches still fail to separate the weighting of indicators from performance evaluation, and it is difficult to determine whether a critical indicator has been able to achieve adequate performance levels [9, 19]. Consequently, existing frameworks may provide multidimensional or aggregated assessments but may not explicitly reveal whether strategically important indicators remain underperforming at the operational level. Therefore, the contribution of the proposed EGL framework lies not merely in combining the three dimensions, but in linking their relative importance with actual operational performance to identify importance–performance mismatches and support coordinated improvement priorities [20]. Within this framework, Fuzzy AHP captures the relative importance of EGL indicators under uncertain expert judgment, whereas TLS identifies their realized performance status; linking these two perspectives provides an importance–performance diagnosis rather than only an aggregated performance score.

The conceptual and methodological gaps become apparent when we consider manufacturing performance in the coffee agroindustry. Coffee processing is characterized by sequential production stages like sorting, roasting, cooling, grinding, and packaging, and the efficiency of the processes in a process is important for productivity and cycle time for operation and stability of production [21]. At the same time, roasting and grinding are energy-intensive processes [22], and coffee processing leaves behind organic residue (husks, grounds, and other products) that are to be used or handled properly or treated properly [23]. In addition, many activities in small- and medium-scale coffee processing remain labor-intensive, including material handling, sorting, packaging, and workstation-based operations, which expose workers to awkward postures, repetitive movements, physical workload, and fatigue [21]. These characteristics show that the coffee agroindustry is not just an empirical subject of study for coffee processing but also a relevant production context for jointly assessing ergonomics, green manufacturing, and lean manufacturing at the operational level. However, previous assessments have generally considered these dimensions separately or in partial combinations rather than linking their relative importance with their realized operational performance within a unified diagnostic framework [19]. Moreover, while AHP and Delphi are both widely used in sustainability and performance assessment, crisp-value-based methods are not appropriate to accurately capture the uncertainty and vagueness of linguistic expert judgment [18]. Therefore, a more reliable weighting approach, such as the Fuzzy Analytical Hierarchy Process (Fuzzy AHP), can offer a way to account for expert judgments that are ambiguous [24]. This is particularly important considering that general sustainability frameworks such as TBL are still strategic and not well translated to functional assessment at the workstation level [8]. Thus, the coffee agroindustry provides an important and challenging framework to develop an integrated EGL assessment, which can be supported by a weighted approach that captures expert judgment uncertainty.

To overcome these limitations, this study proposes an integrated operational-level evaluation framework based on the Ergo-Green-Lean (EGL) model, which combines ergonomics, green manufacturing and lean manufacturing indicators into one manufacturing performance assessment. This approach is grounded in the need to consider these three dimensions jointly when assessing manufacturing performance, particularly because improvements focused exclusively on efficiency may overlook human and environmental considerations [14]. In the proposed framework, Fuzzy Analytical Hierarchy Process (Fuzzy AHP) is used to determine the importance of weights of EGL indicators and to capture uncertainty in expert judgment. The resulting EGL Performance Index represents the overall manufacturing performance and provides a basis for identifying improvement priorities. The novelty of this study is that it provides an integrated operational diagnostic framework that links indicator importance with realized performance to identify importance performance mismatches across human, environmental, and process-efficiency dimensions. The theoretical contribution therefore lies in conceptualizing operational sustainability performance as the correspondence between strategic indicator importance and realized performance across the EGL dimensions, enabling cross-dimensional imbalances to be identified beyond an aggregated performance score. Rather than directly testing causal interactions or trade-offs among the EGL dimensions, the proposed framework provides an integrated diagnostic view of their relative importance and realized performance. This integration allows for a more holistic analysis of production system conditions and supports the formulation of sustainable improvement strategies at the operational level [25].

Based on this background, this work aims to develop an Ergo-Green-Lean (EGL)-based manufacturing performance evaluation framework that assesses the performance of production systems at the operational level. In principle, EGL can serve as a bridge to general and fragmented sustainability assessment techniques, integrating ergonomics, environmental performance and process efficiency in a single framework. In practice,

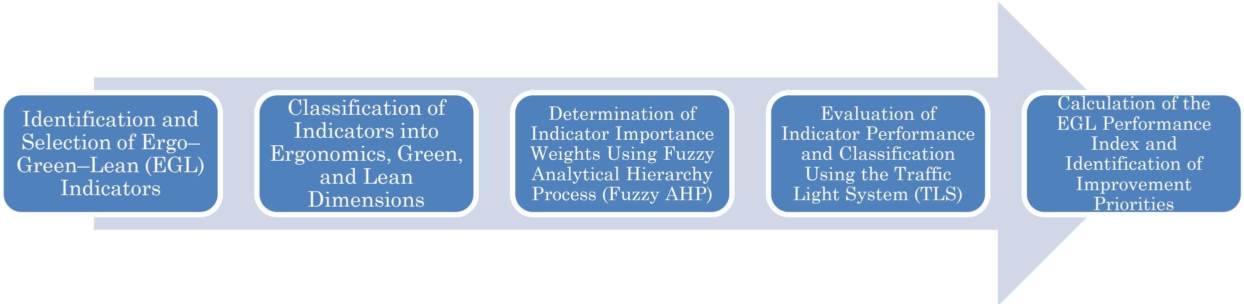

Figure 1. Conceptual framework of the proposed Ergo–Green–Lean (EGL)-based manufacturing performance assessment.

the incorporation of Fuzzy AHP and TLS allows the framework to combine indicator importance weights with actual performance classification. The methodology is applicable to the coffee processing industry as its production is done with sequential production processes and high energy consumption to be generated and organic waste to be produced, and physical workloads are used in different production stages. From an organizational standpoint, the framework helps coffee industry decision-makers to recognize improvement areas of the indicators' significance based on actual performance. This study thus provides a systematic and quantitative framework for manufacturing performance, balancing worker health, environmental responsibility and operational efficiency.

Methods

This section presents the proposed framework for evaluating manufacturing performance by integrating ergonomic, environmental, and operational efficiency dimensions, as illustrated in Figure 1. The framework provides a systematic approach for assessing production system performance at the operational level through five main stages.

The first stage involves the identification and selection of relevant Ergo–Green–Lean (EGL) indicators through a literature review and expert consultation. In the second stage, the selected indicators are classified and structured into three dimensions: ergonomics, green, and lean, representing worker health and safety, environmental performance, and process efficiency, respectively. In the third stage, the relative importance of the indicators is determined by using the Fuzzy Analytical Hierarchy Process (Fuzzy AHP), which accommodates uncertainty and vagueness in expert judgments.

In the fourth stage, the observed performance of each indicator is converted into a comparable efficiency value and classified using the Traffic Light System (TLS) into low, medium, and high-performance categories. Finally, in the fifth stage, the indicator importance weights and efficiency values are integrated to calculate the EGL Performance Index. The resulting index represents the overall manufacturing performance of the production system and provides a basis for identifying performance gaps and priority areas for improvement.

Identification and Selection of EGL Indicators

The EGL indicators were identified through a literature review and expert consultation to ensure their relevance to the coffee agroindustry The expert panel consisted of three academics and practitioners with knowledge of manufacturing performance assessment, ergonomics, green manufacturing, lean manufacturing, and coffee processing. The panel comprised an academic specializing in ergonomics and manufacturing systems with more than 10 years of experience, an academic specializing in lean and sustainable manufacturing with more than 10 years of research experience, and a coffee-processing practitioner with more than 8 years of operational experience. All experts participated in indicator validation and Fuzzy AHP pairwise comparisons. They were purposively selected based on their complementary expertise in the human, environmental, and operational dimensions of the EGL framework. The use of three experts was considered appropriate because the assessment relied on purposive expert judgment rather than statistical representation, with the panel providing complementary expertise across the EGL dimensions. The adequacy of the judgments was further supported by the acceptable consistency ratio and the stability of the results under sensitivity analysis. An FGD was conducted to validate the selected indicators and consolidate the experts' pairwise judgments. Differences in judgments were discussed until a consensus linguistic judgment was reached for each pairwise comparison, which was subsequently converted into triangular fuzzy numbers to construct the final pairwise comparison matrices. The case company was purposively selected

Table 1. EGL indicators and measurement formulas

Dimension	Indicator	Input	Equation	References
Lean	Cycle time	TE = Time efficiency VAT = Total value-added time $\mathrm{VAT_i}$ = Value-added time at production stage i NVAT = Total non-value-added time $\mathrm{NVAT_i}$ = Non-value-added time at production stage i TT = Total processing time i = Index of production stage, $i = 1,2,\ldots,n$ n = Total number of production stages	$\mathrm{TE} = \frac{\mathrm{VAT}}{\mathrm{TT}}$ $\mathrm{VAT} = \sum_{\mathrm{i=1}}^{\mathrm{n}} (\mathrm{VAT}_i)$ $\mathrm{NVAT} = \sum_{\mathrm{i=1}}^{\mathrm{n}} (\mathrm{NVAT}_i)$ $\mathrm{TT} = \mathrm{VAT} + \mathrm{NVAT}$	[26-28]
	Inventory level	IE = Inventory efficiency NI = Total inventory TM = Total materials	$\mathrm{IE} = \frac{\mathrm{NI}}{\mathrm{TM}}$	[27, 29]
	Defect rate	DE = Defect efficiency N_d = Defective products N_p = Total products	$DE = 1 - \left(\frac{N_d}{N_p}\right)$	[3]
	Process efficiency	PE = Process efficiency VAT = Total value-added time NVAT = Total non-value-added time	$\mathrm{PE} = \frac{VAT}{VAT + NVAT}$	[30]
Green	Material consumption efficiency	ME = Material efficiency VAM = Total materials used in value-added activities VAM_i = Materials used in value-added activities at production stage i NVAM = Total materials used in non-value-added activities $\mathrm{NVAM_i}$ = Materials used in non-value-added activities at production stage i TM = Total materials	$ME = \frac{VAM}{TM}$ $VAM = \sum_{i=1}^{n} (VAM_i)$ $NVAM = \sum_{i=1}^{n} (NVAM_i)$ $TM = VAM + NVAM$	[26]
	Energy consumption	EE = Energy efficiency VAE = Total energy used in value-added activities $\mathrm{VAE_i}$ = Energy used in value-added activity at production stage i NVAE = Total energy used in non-value-added activities $\mathrm{NVAE_i}$ = Energy used in non-value-added activity at production stage i TE = Total energy	$\mathrm{EE} = \frac{\mathrm{VAE}}{\mathrm{TE}}$ $\mathrm{VAE} = \sum_{\mathrm{i=1}}^{\mathrm{n}} (\mathrm{VAE}_i)$ $\mathrm{NVAM} = \sum_{\mathrm{i=1}}^{\mathrm{n}} (\mathrm{NVAE}_i)$ $\mathrm{TE} = \mathrm{VAE} + \mathrm{NVAE}$	[26]
	Water consumption	WCE = Water consumption efficiency AW = Amount of water used TW = Total water	$WCE = \frac{AW}{TW}$	[30]
	Waste recycling / utilization	WRE = Waste recycling/utilization efficiency WL = Amount of landfilled waste TWG = Total waste generated	$WRE = 1 - \frac{WL}{TWG}$	[31]
Ergonomics	Musculoskeletal risk level	N_{MSD} = workers reporting musculoskeletal complaints N_{total}= total workers assessed	$MSE = 1 - \left(\frac{N_{MSD}}{N_{total}}\right)$	[32]
	Physical workload / Fatigue	$\mathrm{T_2}$ = score for slight bending (45° forward) $\mathrm{T_3}$ = score for very bent (75° forward) $\mathrm{T_4}$ = score for entangled $\mathrm{T_5}$ = score for sideways hunchback A_2 = score for one arm above the shoulder A_3 = score for both arms above the shoulder L_3 = score for squatting (15° forward) L_4 = score for kneeling on one or two feet L_5 = score for walking or moving W_{u1} = score for lifting/carrying loads perpendicularly (<10kg) W_{u2} = score for lifting/carrying perpendicular loads (10-20kg) W_{u3} = score for lifting/carrying perpendicular loads (>20kg) W_{i1} = score lifting/carrying bending loads (<10kg) W_{i2} = score lifting/carrying bending loads (10-20kg) W_{i3} = score for lifting/carrying bending loads (>20kg)	$\mathrm{PLI} = 0.974\mathrm{T_2} + 1.104\mathrm{T_3} + 0.068\mathrm{T_4} + 0.173\mathrm{T_5} + 0.157\mathrm{A_2} + 0.314\mathrm{A_3} + 0.405\mathrm{L_3} + 0.152\mathrm{L_4} + 0.152\mathrm{L_5} + 0.549\mathrm{W_{u1}} + 1.098\mathrm{W_{u2}} + 1.647\mathrm{W_{u3}} + 1.777\mathrm{W_{i1}} + 2.416\mathrm{W_{i2}} + 3.056\mathrm{W_{i3}}$	[19]
	Work posture assessment	Quick exposure Check (QEC)	$QEC = 1 - \left(\frac{Score\ QEC}{176}\right)$	[33]
	Occupational safety Level	NR = number of work accidents N_{ac} = total observed activities	$OSL = 1 - \left(\frac{NR}{N_{ac}}\right)$	[31, 34]

Table 2. Linguistic scale and triangular fuzzy numbers used in Fuzzy AHP

Linguistic variable	Description	Triangular fuzzy number	Reciprocal
EI	Equally important	(1, 1, 1)	(1, 1, 1)
I(EI–MI)	Intermediate between EI and MI	(1/2, 1, 3/2)	(2/3, 1, 2)
MI	Moderately more important	(1, 3/2, 2)	(1/2, 2/3, 1)
I(MI–SI)	Intermediate between MI and SI	(3/2, 2, 5/2)	(2/5, 1/2, 2/3)
SI	Strongly more important	(2, 5/2, 3)	(1/3, 2/5, 1/2)
I(SI–VS)	Intermediate between SI and VS	(5/2, 3, 7/2)	(2/7, 1/3, 2/5)
VS	Very strongly more important	(3, 7/2, 4)	(1/4, 2/7, 1/3)
I(VS–ES)	Intermediate between VS and ES	(7/2, 4, 9/2)	(2/9, 1/4, 2/7)
ES	Extremely more important	(4, 9/2, 9/2)	(2/9, 2/9, 1/4)

because its sequential operations, manual activities, resource use, and waste generation were relevant to EGL assessment.

The selected indicators were grouped into lean, green, and ergonomics dimensions, representing operational efficiency, environmental performance, and employee well-being, respectively. To ensure consistent and reproducible performance measurement, each indicator was operationalized using a specific measurement formula derived from the relevant literature. Table 1 summarizes the EGL indicators and corresponding measurement formulas.

The lean indicators assess process efficiency, waste, and production-flow performance, while the green indicators evaluate resource consumption and waste utilization. The ergonomics indicators assess worker-related risks associated with physical workload, posture, musculoskeletal conditions, and occupational safety. Together, these indicators provide an operational basis for evaluating the three dimensions of the EGL framework.

Indicator Weighting Using Fuzzy Analytical Hierarchy Process (Fuzzy AHP)

To evaluate the importance weights of indicators, the analysis was conducted using the Fuzzy Analytical Hierarchy Process (Fuzzy AHP) method within the Ergo–Green–Lean (EGL) framework. This approach is an extension of classical AHP that supports the subjective evaluation of experts by considering uncertainty and vagueness using fuzzy numbers [18]. The weighting process began by developing a hierarchical structure consisting of the research goal, EGL dimensions, and performance indicators, followed by pairwise comparisons among the indicators [35].

Pairwise comparisons among indicators were performed using a linguistic scale, which was then converted into Triangular Fuzzy Numbers (TFNs). A generic TFN is denoted by $\tilde{x} = (l, m, u)$, where l, m and u denote the lower, middle, and upper values, respectively. The linguistic variables, corresponding TFNs, and reciprocal values used in the pairwise comparisons are presented in Table 2.

The fuzzy pairwise comparison matrix is then expressed as follows:

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & 1 \end{bmatrix} \tag{1}$$

Where $\tilde{A}$ denotes the fuzzy pairwise comparison matrix and $\tilde{a}_{ij} = (l_{ij}, m_{ij}, u_{ij})$ denotes the fuzzy comparison value of criterion i relative to criterion j. Here l_{ij}, m_{ij} and u_{ij} represent the lower, modal, and upper values of $\tilde{a}_{ij}$, respectively $i, j = 1,2, \dots, n$; and n denotes the number of criteria or indicators being compared. The reciprocal relationship is defined as:

$$\tilde{a}_{ij} = \left(\frac{1}{u_{ij}}, \frac{1}{m_{ij}}, \frac{1}{l_{ij}}\right) \tag{2}$$

Before calculating the indicator weights, the consistency of the pairwise comparison judgments were evaluated using the modal values of the triangular fuzzy numbers. The Consistency Ratio (CR) was calculated, with CR < 0.10 indicating acceptable consistency. This consistency check was performed prior to the fuzzy weighting procedure to ensure that the underlying pairwise judgments were sufficiently coherent. Subsequently, the indicator weights were calculated using the extent analysis method developed by Chang [36]. The synthetic extent value for each indicator was calculated as follows:

$$S_i = \sum_{j=1}^{n} \tilde{a}_{ij} \times \frac{1}{\sum_{i=1}^{n} \sum_{j=1}^{n} \tilde{a}_{ij}} \tag{3}$$

To compare two fuzzy numbers, $M_1 = (l_1, m_1, u_1)$ and $M_2 = (l_2, m_2, u_2)$, the degree of possibility was used as follows:

$$V(M_1 \geq M_2) = \begin{cases} 1, & if\ m_1 \geq m_2 \\ 0, & if\ l_2 \geq u_1 \\ \frac{l_2 - u_1}{(m_1 - u_1) - (m_2 - l_2)}, & otherwise \end{cases} \tag{4}$$

The minimum value of the degree of possibility for each indicator was then calculated to obtain the initial weight vector:

$$d'(A_i) = \min V(S_i \geq S_j), \qquad i \neq j \tag{5}$$

The weights were then normalized to obtain the final weights:

$$W_i = \frac{d'(A_i)}{\sum_{i=1}^{n} d'(A_i)} \tag{6}$$

If the weights remained in fuzzy form, defuzzification was performed using the centroid method:

$$W_i = \frac{l_i + m_i + u_i}{3} \tag{7}$$

The final weights obtained represent the relative importance of each indicator in the production system and were subsequently used in the calculation of the EGL performance index.

Performance Evaluation and Measurement of EGL Performance Index

The Ergo–Green–Lean Performance Index (EGL Index) was developed as a composite index to represent the overall manufacturing performance of the production system. This index is derived by multiplying each indicator's efficiency value by its importance weight [19]. The EGL Index was used to identify priority areas for improvement and support decision-making related to production system enhancement.

$$EGL = \sum_{i}^{n} Wi \times Ei \tag{8}$$

where W_i denotes the weight of the i-th indicator, E_i denotes the efficiency value of the i-th indicator, and n represents the total number of indicators. This index reflects the performance level of the production system in the coffee processing industry up to the ground coffee milling stage.

To facilitate interpretation, the EGL Index is classified using the Traffic Light System (TLS), namely red (<60%), indicating low performance; yellow (60%–90%), indicating that improvement is required; and green (>90%), indicating good performance. These thresholds were adopted from previous manufacturing sustainability assessment research [30]. These thresholds were used only as descriptive classification criteria and were not involved in calculating the EGL Performance Index. Therefore, the continuous performance values remain the primary basis for comparing indicators and dimensions, while the TLS categories provide an additional visual interpretation of performance status.

Results and Discussions

The Case

The proposed EGL framework was applied to a coffee-processing company characterized by sequential production stages, substantial manual activities, resource and energy consumption, and processing waste generation. These characteristics provided an appropriate setting for evaluating operational efficiency, environmental performance, and worker well-being simultaneously. The assessment involved 12 indicators grouped into three dimensions: lean, green, and ergonomics.

The relative importance of the EGL dimensions and indicators was determined using Fuzzy AHP based on pairwise judgments from three purposively selected experts. Expert judgments were expressed using the predefined linguistic scale and converted into triangular fuzzy numbers. The fuzzy pairwise comparison matrices for the EGL dimensions and indicators are presented in Tables 3–6. The matrices were subsequently processed using Chang's extent analysis to obtain local and global weights. The resulting weights were then combined with the normalized performance values of each indicator to calculate the EGL Performance Index and classify performance using the Traffic Light System (TLS).

Table 3. Fuzzy AHP pairwise comparison matrix for EGL dimensions

Dimension	Lean	Green	Ergonomic
Lean	EI	I(EI-MI)	1/I(EI–MI)
Green		EI	1/I(EI–MI)
Ergonomic			EI

Table 4. Fuzzy AHP pairwise comparison matrix for lean indicators

Indicator	Cycle time	Inventory level	Defect rate	Process efficiency
Cycle time	EI	I(EI–MI)	I(EI–MI)	1/I(EI–MI)
Inventory level		EI	1/I(EI–MI)	1/MI
Defect rate			EI	1/I(EI–MI)
Process efficiency				EI

Table 5. Fuzzy AHP pairwise comparison matrix for green indicators

Indicator	Material consumption efficiency	Energy consumption	Water consumption	Waste recycling / utilization
Material consumption efficiency	EI	1/I(EI–MI)	I(EI–MI)	I(EI–MI)
Energy consumption		EI	MI	I(EI–MI)
Water consumption			EI	1/I(EI–MI)
Waste recycling / utilization				EI

Table 6. Fuzzy AHP pairwise comparison matrix for Ergonomics indicators

Indicator	Musculoskeletal risk level	Physical workload / fatigue	Work posture assessment	Occupational safety level
Musculoskeletal risk level	EI	I(EI–MI)	I(EI–MI)	MI
Physical workload / fatigue		EI	I(EI–MI)	I(EI–MI)
Work posture assessment			EI	I(EI–MI)
Occupational safety level				EI

Table 7. Global weight of EGL indicators in coffee processing system

Dimension	Weight	Indicator	Local weight	Global weight
Lean	0.34	Cycle time	0.28	0.09
		Inventory level	0.18	0.06
		Defect rate	0.22	0.08
		Process efficiency	0.32	0.11
Green	0.30	Material consumption efficiency	0.27	0.08
		Energy consumption	0.30	0.09
		Water consumption	0.20	0.06
		Waste recycling / utilization	0.23	0.07
Ergonomics	0.36	Musculoskeletal risk level	0.31	0.11
		Physical workload / fatigue	0.27	0.10
		Work posture assessment	0.23	0.08
		Occupational safety level	0.18	0.07

Indicator Weight Assessment Results

The indicator weights were obtained using the Fuzzy AHP method. The consistency of the pairwise comparisons were evaluated using the Consistency Ratio (CR), which yielded a value of 0.09. Since this value is below the acceptable threshold of 0.10, the expert judgments were considered sufficiently consistent for the weighting analysis. A sensitivity analysis was conducted by varying each indicator's weight individually by ±5% and ±10%. After each variation, all weights were renormalized to maintain a total weight of one, and both the EGL Performance Index and the ranking of improvement priorities were recalculated. The resulting index ranged from 67.72% to 67.88% for the ±5% variation and from 67.64% to 67.96% for the ±10% variation, with all scenarios remaining in the medium TLS category. The ranking of the main improvement priorities also showed no substantial changes across the tested scenarios, indicating that the assessment remained robust to moderate variations in the expert-derived weights. As shown in Table 7, the ergonomics dimension received the highest weight of 0.36, followed by leaning at 0.34 and green at 0.30. This result indicates that human-related aspects are considered the most critical dimension in assessing production system performance in the coffee processing context, particularly because this sector still relies heavily on labor-intensive activities. This finding is consistent with Karuppiah, et al. [37], who emphasized that ergonomic factors play an important role in improving worker health and productivity in small-scale industries.

At the indicator level, process efficiency and musculoskeletal risk level obtained the highest global weights, each at 0.11, followed by physical workload/fatigue at 0.10. These results show that coffee processing performance is strongly influenced by both process-flow efficiency and workers' physical conditions. In the lean

Table 8. Efficiency scores and TLS classification of EGL indicators in the coffee processing system

Dimension	Indicator	Efficiency	Level of performance
Lean	Cycle time	68%	
	Inventory level	62%	
	Defect rate	74%	
	Process efficiency	70%	
Green	Material consumption efficiency	72%	
	Energy consumption	65%	
	Water consumption	78%	
	Waste recycling / utilization	91%	
Ergonomics	Musculoskeletal risk level	58%	
	Physical workload / fatigue	60%	
	Work posture assessment	55%	
	Occupational safety level	70%	

dimension, process efficiency is the main priority because sequential coffee processing requires smooth material flow from sorting to grinding. This finding aligns with lean principles, where waste elimination is central to productivity improvement [11] and is supported by lean–ergonomics studies showing improvements in efficiency and cycle time [38].

The green dimension was dominated by energy consumption and material consumption efficiency, with global weights of 0.09 and 0.08, respectively. This is relevant, as roasting and grinding require large amounts of energy and material efficiency affect production costs and environmental performance. This finding is in agreement with green-lean manufacturing research that indicates the importance of resource management as a key driver of environmental performance [39]. In the ergonomics dimension, musculoskeletal risk level and physical workload/fatigue were the key factors as manual labor, sorting and packaging are associated with repetitive motion, poor posture and fatigue in workers. Musculoskeletal disorders are well recognized as important factors affecting the productivity [40] and health of workers and also important criteria for fuzzy ergonomic assessment [41].

Overall, the weighting results indicate that improvement priorities in coffee processing need to be focused on process efficiency, ergonomic risk reduction, workload management, and resource-use efficiency. These results illustrate the value of an integrated EGL approach because improvement priorities span human, environmental, and operational dimensions and should therefore be assessed within a common diagnostic framework [42]. The Fuzzy AHP weights provide the strategic importance structure that can be compared with actual performance results to identify priority gaps and improvement actions.

Results of Efficiency Indicators

The results of the indicator performance evaluation are presented in Table 8, and most indicators are of medium category (60%-90%). In this case, the production system in the coffee processing industry has achieved a moderate performance level but still needs improvement to reach a higher level. This is common in small and medium-sized industries in which resources are limited and there is no standard work style [9]. Importantly, these performance scores represent the realized operational condition of each indicator and should be interpreted separately from the relative importance of weight obtained through Fuzzy AHP.

All indicators in the lean dimension fall within the medium category, indicating that basic process-efficiency practices have been implemented but substantial opportunities remain for waste reduction. This indicates that further reductions in cycle time, inventory level, and defect rate are required to achieve higher operational efficiency. This finding aligns with the lean manufacturing concept that ever-eliminating waste is a continuous process; optimal condition may never be fully reached in an early stage [43]. Furthermore, research with production efficiency has shown that implementing lean can lead to a more significant effect when it is combined with ergonomics [38].

The green dimension shows relatively better performance than the other dimensions. The waste recycling/utilization indicator falls within the high category (>90%), indicating that waste generated from coffee processing has been utilized effectively. However, other indicators, such as energy, water, and material consumption, remain in the medium category, suggesting that resource use efficiency has not yet been optimized. This condition indicates that environmental sustainability practices in coffee processing

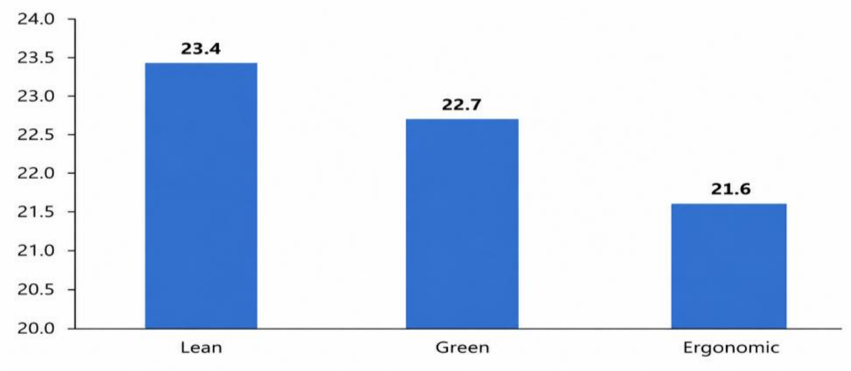

Figure 2. Index performance for each EGL Dimension

industry tends to remain partial, focusing more on waste management than on improving resource use efficiency throughout the production process. This finding is in line with green–lean manufacturing studies, which emphasize that waste management and resource efficiency are key indicators of industrial environmental performance [39].

The ergonomics dimension exhibits the lowest overall performance. Several indicators, particularly musculoskeletal risk level and work posture, fall within the low category (<60%), indicating substantial work-related risks that may affect worker health, productivity, and process stability. While the production system can function, this indicates that awareness of working conditions has not been prioritized. These results are in accordance with another study, which reported a high prevalence of MSDs among coffee pickers [44]. In addition, limited attention to ergonomics can directly affect productivity decline and increased work fatigue [45].

Overall, these results indicate an imbalance in performance across dimensions. Operational and environmental aspects are relatively stable, whereas ergonomics remains underdeveloped. Therefore, improving production system performance in the coffee processing industry requires not only lean and green improvements but also systematic ergonomic interventions.

EGL Performance Index in the Coffee Industry

The EGL Performance Index in coffee processing industry is 67.7%, which is in medium category based on Traffic Light System (TLS) classification. Figure 2 shows the contribution of each dimension to the EGL Performance Index. The lean dimension provides the highest realized contribution to the EGL Performance Index at 23.4%, followed by green at 22.7% and ergonomics at 21.6%. This shows that lean and green currently make greater realized contributions to the overall EGL performance than ergonomics, rather than indicating that they are strategically more important. In line with studies, lean implementation is important in reducing waste, speed of processes and better use of production resources in terms of efficiency [3].

Dimensional differences indicate that production system performances have not developed in a balanced form. Ergonomics receives the highest strategic importance weight in the Fuzzy AHP analysis but produces the lowest realized contribution to the EGL Performance Index. This mismatch indicates that the dimension considered most important by the experts has not achieved a correspondingly high level of operational performance. This indicates a recognition–implementation gap, where ergonomics is considered important but receives less operational attention than immediate production and efficiency targets. In labor-intensive processing, limited attention to work posture and physical workload may therefore sustain ergonomic risks and potentially affect process stability. This is a common scenario in lean-green-ergonomics integration with ergonomics being often overlooked during implementation because it has no direct impact on short-term productivity [12].

From the systems point of view, the 67.7% value of the index represents a transitional performance condition. The system has some basic operational stability but has not yet reached the point where integration is optimal in terms of EGL dimensions. The imbalance indicates that performance improvement can't be achieved only in terms of efficiency; it needs to be achieved in a fashion that combines ergonomic, environmental, and operational aspects at the same time [43]. The present analysis does not directly quantify interactions or trade-offs among the three dimensions; instead, it provides an integrated diagnostic assessment that identifies mismatches between their strategic importance and realized performance. The integration of all three dimensions in sustainable manufacturing systems is also considered a key driver of sustainable performance [46].

Overall, these results imply that manufacturing performance improvement in the coffee processing industry should not be limited to optimizing one dimension. The medium EGL Performance Index should be taken as evidence of further improvement opportunities, especially in ergonomics. Priority actions should thus be taken to minimize ergonomic risks, improve work posture, manage physical workload, and sustain process and resource efficiency, to achieve a more balanced EGL performance.

Conclusion

This study constructs a three-dimensional manufacturing performance evaluation framework covering ergonomics, green practices, and lean manufacturing (EGL). The fuzzy analytic hierarchy process is used to assign weights to each indicator, and a traffic light system is adopted to divide performance levels. The study finds that the performance of the coffee processing system is at a medium level, and the integration of the three dimensions has not yet been optimized. Conceptually, this study contributes to manufacturing performance evaluation by integrating human, environmental, and operational aspects within a single framework. The proposed EGL framework provides a structured basis for identifying performance gaps and improvement priorities across these dimensions. From a management perspective, efforts are needed to reduce physical workload, improve workplace conditions, and strengthen occupational safety, while maintaining the advantages of operational efficiency and environmental performance.

This study has several limitations. The framework was applied to a single coffee-processing company and should therefore be regarded as an initial application and proof-of-concept rather than comprehensive validation. Consequently, the general applicability of the EGL framework, indicator structure, and resulting improvement priorities requires further examination across multiple coffee-processing companies and operational contexts. The weighting process also relied on expert judgment, although Fuzzy AHP was used to address uncertainty in the evaluation. In addition, the assessment was static and did not capture performance changes over time.

Future research should validate the framework across multiple companies, production scales, and agro-industrial sectors using more diverse expert groups. Further studies may also compare Fuzzy AHP with other multi-criteria decision-making methods and conduct longitudinal assessments to examine changes in EGL performance following improvement interventions.

Acknowledgment

The authors would like to express their sincere gratitude to Universitas Muhammadiyah Malang for the support and facilities provided during the completion of this research. The authors also appreciate the contributions of all parties involved, particularly those who participated in data collection and provided valuable insights throughout the study.

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