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RESEARCH ARTICLE

Promoting sustainable wastewater treatment operations: The role of lean practices and lean six sigma enablers

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ABSTRACT - This study investigates the influence of Lean Six Sigma enablers (LSS_En), comprising strategy, environment, culture, resource, and linkage based on Sustainable Performance (Sus_Perf) in wastewater treatment plants of Malaysian and Multi-national Companies (MNCs), using data from 276 respondents. Additionally, the study examines the intervening impact of lean practices (LPs), specifically statistical process control, human resource management, and total productive maintenance, on this relationship. Employing partial least squares structural equation modelling, the analysis demonstrates a positive and significant impact of LSS_En on Sus_Perf, with $\beta = 0.406$, $p = 0.001$ for Malaysian companies, and $\beta = 0.608$, $p = 0.001$ for MNCs. Furthermore, the impact of LSS_En on LPs is also significantly positive in both types of companies, with $\beta = 0.544$, $p = 0.001$ for locals, and $\beta = 0.546$, $p = 0.001$ for MNCs, respectively. However, the relationship between LPs and Sus_Perf is insignificant in MNCs, with $\beta = 0.126$, $p > 0.05$, while Malaysian companies show a stronger impact with $\beta = 0.418$, $p = 0.001$. Multi-group analysis confirms that local companies excel in H3 with a significant difference of 0.289, $p = 0.043$. However, the intervening role of LPs in H4 shows no significant difference between the two company types in the LSS_En and Sus_Perf relationship when $p > 0.05$. This research highlights the scarcity of studies exploring the impact of LSS enablers on sustainable performance in Malaysian wastewater treatment plants and emphasizes the role of LPs by focusing on ownership contributions.

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1. INTRODUCTION

The substantial waste produced by manufacturing processes has become a global concern, especially given our limited resources. A significant waste stream is wastewater, which poses a major challenge for industries requiring multiple treatment stages. Unfortunately, inadequate treatment and direct discharge of wastewater are common, leading to global water body contamination [1]. The 2030 Agenda for sustainable development, adopted by all United Nations member states in 2015, emphasizes 17 Sustainable Development Goals, including clean water and sanitation targets. By 2050, global clean water demand will rise by 55%, supporting 2.7 billion more people [2]. Meeting water needs for domestic, agricultural, and industrial use requires efficient management and cleaner technologies. Sustainability performance (Sus_Perf) measures a system's ability to meet current needs while preserving future generations' ability to do the same [3]. Wastewater treatment plants (WWTPs) are important for environmental sustainability, purifying wastewater before releasing it into natural water bodies [4]. Moreover, lean six sigma (LSS) integrates sustainability, ensuring process improvements consider long-term environmental and social impacts [5,6]. Initially focused on manufacturing efficiency [7], Lean Six Sigma now also reduces resource consumption and waste [8]. LSS is an improvement approach that targets better management practices and waste reduction within organizations. It integrates six sigma and lean methodologies, which originated from Motorola Corporation and the Toyota Production System, respectively. LSS aims to streamline waste processing and boost efficiency [9]. Both lean and six sigma share common traits like continuous improvement, customer satisfaction, and employee involvement [10]. LSS can improve business operations, including productivity, quality, and cost management [11].

Incorporating sustainability into LSS projects provides a holistic approach that encompasses all dimensions of sustainability [12]. The framework by Erdil et al. [13] incorporates sustainability into the LSS and Defines, Measures, Analyses, Improves, and Controls, known as the DMAIC cycle, allowing organizations to address sustainability issues throughout the project lifecycle. Studies by Cherrafi et al. [14] and Ben Ruben et al. [15] demonstrate this integration enhances efficiency and sustainability across economic, environmental, and social dimensions. Social performance acknowledges humans' significance in various aspects, including working conditions, improved relationships, communication, and reduced community disruption [16]. Barcia et al. [17] found that community quality of life and workplace safety indicators were achieved in the reviewed papers. Social performance is closely related to LPs such as human resource management (HRM), which can enhance employees' sense of accomplishment, team spirit, and organizational learning. This encompasses employees' problem-solving abilities, learning from past experiences, and

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knowledge sharing with others. Additionally, employee satisfaction with their workplace, physical well-being, and skills can benefit from active participation in customer relations, human resource practices, and product design [18].

Cherrafi et al. [14] studied four Moroccan industrial sectors, applying lean practices such as 5S, kaizen, value stream mapping, just-in-time, statistical process control (SPC), total productive maintenance (TPM), plan-do-check-act, and supplier-input-process-output-control, to address energy, water, material conservation, waste reduction, risk assessment, workplace safety, and cost reduction. The United States Environmental Protection Agency emphasizes the benefits of integrating LSS with environmental considerations, promoting eco-friendly processes [19]. This integration leads to cleaner production and a healthier environment by reducing negative impacts on manufacturing and services [20]. The natural resource-based view theory was selected as a theoretical guideline for this research because it explains the elements of environmental-centric LSS enablers and sustainable outcomes [21]. Moreover, Kaswan and Rathi [22] argue that the environmental-centric LSS enablers minimize environmental waste and conserve resources. However, managers hesitate to adopt LSS due to a lack of readiness measures, limited resources, and fear of failure [23,24]. Additionally, enabling factors are crucial for smooth operations, especially in dynamic processes such as WWTPs [25]. To implement LSS and promote sustainable development while upholding environmental stewardship in WWTPs, it is crucial to adopt these enabling factors based on their impact and driving characteristics [26]. Given the theoretical and practical gaps, this study would like to address the research question: “What is the impact of LSS enablers on the current WWTP sustainability performance in Malaysia?”. In addition, Godinho Filho et al. studied the application of three LPs, SPC, HRM, and TPM, in 16 industries [27]. The study aimed to measure operational performance using indicators such as stock levels and operational costs. The findings revealed a positive relationship between the implemented LPs and operational performance. However, this study did not empirically examine the collective relationship of LPs on Sus_Perf. In a subsequent study conducted by Negrão et al. [28], the research was expanded by adding seven more LPs and evaluating their impact on operational performance. However, in this study, environmental performance was measured as a single construct, and the proposed model showed a positive result for the impact of LPs on environmental performance. To explore the relationships between practical LPs in WWTPs and their sustainability performance, another research question was developed: “How do the LSS enablers impact the implementation of LPs in current WWTP operations?” “How does the implementation of LPs impact the WWTP sustainability performance?”, and “What is the role of LPs implementation in mediating the relationship between LSS enablers and sustainability performance?”.

Sunder [29] analyzed the top barriers to deploying LSS. A Pareto analysis of the reasons for failure identified four main factors: lack of top management involvement, incorrect project selection, narrow project perspectives, and lack of ownership during deployment. Timans et al. [30] argued that frequent changes in SME ownership led to shifts in management and priorities, making ownership a critical factor for LSS project sustainability. Typically, managers are assigned to new LSS projects after completing a project, resulting in a lack of focus on completed projects. Although LSS includes the “Control” phase to sustain results, lack of ownership often leads to failure. In such cases, processes tend to revert to old habits, challenging the sustainability of LSS benefits. Thus, ownership is crucial to maintaining the results of successful projects [31]. Additionally, to examine the impact of ownership types, this study investigates the significant differences between locally owned and multinational companies, adding a novel aspect to the research.

2. MATERIALS AND METHODS

Various LSS_En play a crucial role in successful strategy implementation. According to the LSS_En framework proposed by Singh et al. [9], there are five groups of enablers: strategy, environment, culture, resource, and linkage-based. This study uses the reflective measurement items to assess each enabler's formative higher-order latent constructs. In the strategy-based category, top management involvement is essential [22], as it allocates key resources [32]. Effective project leadership motivates employees to embrace LSS principles [33], and providing rewards and incentives increases employee commitment to adopting LSS practices [9,34]. Additionally, supportive organizational culture [35], effective performance measurement [36], and consistent with accurate data collection [37] are among the measurement items within this latent construct. In the environment-based enabler, initiatives such as carbon reduction [21], eco-friendly packaging, government incentives [37], an green product design contribute to environmental sustainability, while environmentally friendly transportation systems reduce carbon emissions [38]. Additionally, stakeholder pressure for eco-friendly products and services [9] serve as a measurement item for this latent construct. Furthermore, seven additional measurement items were employed to measure the culture-based latent construct. Among these, the selection and retention of skilled employees, teamwork, and inter-departmental communication facilitate LSS implementation. Cultivating a favourable culture, promoting efficient communication, effective scheduling, employee empowerment, sharing project success stories, and maintaining a positive organizational culture are crucial for sustainable programs [32-34].

Five additional measurement items, comprising a good training program, proper project prioritization, effective resource allocation, sharing financial benefits among employees, and understanding of environmental LSS methodology, are essential to measuring the reflective latent construct of resource-based enablers [12, 33, 34, 36, 37]. Finally, to complete the LSS_En, another five measurement items, consisting of linking LSS to core business processes [39], buyer-supplier relationships [33], prioritizing customer satisfaction, and understanding customer demand [9], are crucial for successful implementation [40]. Aligning LSS features with core business [34] leads to cost reduction, eco-friendly processes, and increased market share [41]. This study employs established measurement scales for reflective-reflective LP latent constructs, including HRM [18], SPC [3,6], and TPM [4,5], to assess their impact on reflective-formative

Sus_Perf indicator as defined by Iranmanesh et al. [43] (economic = Eco_Perf, environmental = Env_Perf, and social = Soc_Perf). The measurement instrument was validated through expert panel consultation before the pre-test and pilot study. A quantitative method was used to evaluate all variables in the hypothesis model. Participants were certified professionals known as Competent Person (CP) regulated under Section 49_A, Environmental Quality Act 1974 [44], with at least three years of experience working at WWTPs. They were selected for their expertise in daily quality control management tasks. The questionnaire incorporated modified scales from previous research. Participants rated their agreement with statements on a scale of 1 (Strongly Disagree) to 5 (Strongly Agree) to measure the importance of every measurement item related to LSS_En. For SPC, they indicated the level of implementation from 1 (No implementation) to 5 (Complete implementation). To measure Sus_Perf, they assessed the achievement level on a scale of 1 (Not at all) to 5 (Significant). Using a simple random sampling technique, a list of potential respondents was collected from the National Registry of Certified Environmental Professionals database. Six hundred twenty-five CPs were approached, and permission was obtained from the Environmental Institute of Malaysia. CPs received an online questionnaire and were not obliged to participate.

Hence, to address the research questions discussed above, this study aims to investigate the relationship between LSS_En and Sus_Perf by examining the potential mediating effect of practical LPs in WWTP operations. Four hypotheses were developed based on the conceptual framework provided in Figure 1. The hypotheses are as follows:

H1: There is a significant positive impact of LSS enablers on WWTP sustainable performance.

H2: LSS enablers have a significant positive impact on WWTP Lean practices.

H3: LPs implementation has a significant positive impact on WWTP sustainable performance.

H4: LPs mediate the relationship between LSS enablers and WWTP sustainable performance.

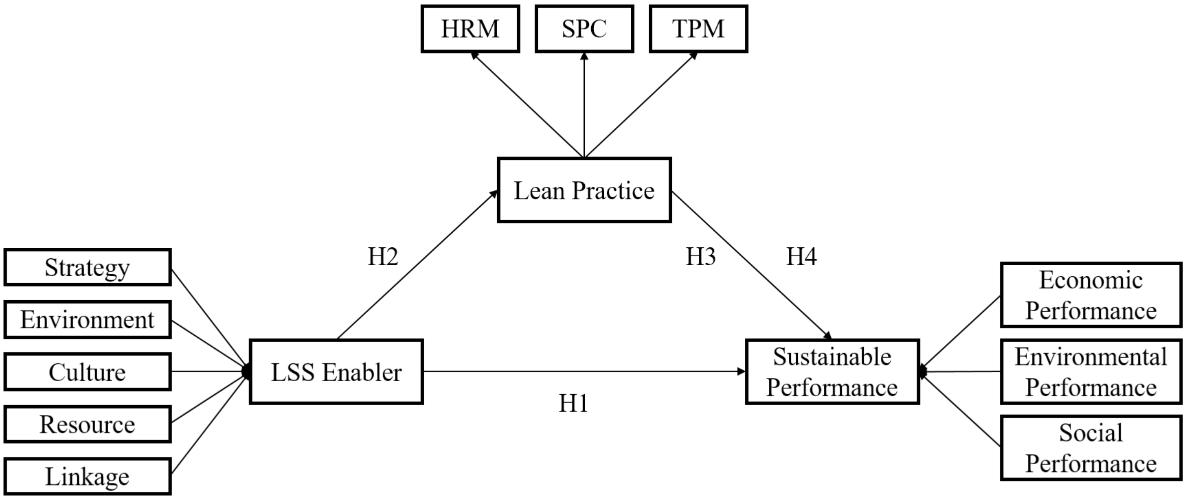

Figure 1. Conceptual framework and hypotheses

The analysis began with data screening and descriptive analysis using IBM SPSS 27.0 software, followed by measurement model and structural model assessment using SmartPLS 4 software. To assess relationships, partial least squares structural equation modelling (PLS-SEM) was employed for its suitability in theory prediction and relationship exploration, rather than covariance-based SEM (CB-SEM), which is used for theory confirmation. This choice was made because the research is pioneering in the WWTP domain. Data analysis included exploring demographic variables and assessing the differences between local, MNC, and complete samples in their hypothesized relationships. The model was then verified using a two-stage embedded analytical approach for reflective and formative constructs [45]. PLS-SEM is advantageous as it evaluates the measurement and structural models, making it well-suited for multi-group analysis.

The first stage involves testing the reflective and formative measurement model for lower and higher-order constructs to assess construct reliability, convergent validity, and discriminant validity used in this study. Composite reliability (CR) and Cronbach's Alpha (α) greater than 0.7 were used to assess construct reliability, which is better suited for PLS-SEM [46]. Convergent validity was evaluated using Average Variance Extracted (AVE), which must be greater than 0.5 for each construct. For discriminant validity, the Heterotrait-Monotrait ratio (HTMT) was used [47]. The significant *p*-value of outer weights, outer loading greater than 0.5, and a variance inflation factor (VIF) below 5 are used to assess multicollinearity issues in formative higher-order constructs. The overall hypothesized model must show a Goodness of Fit meeting the minimum global criterion of 0.3.

The second stage involves testing the hypotheses by examining the structural model. This model defines the causal relationships among the study's constructs, including the coefficient of determination, $R^{2,}$ and path coefficients. The path coefficients (β and *p*-value) indicate how much the data supports the proposed model [45]. To determine the significance of the path coefficients, the bootstrap method was employed with 5000 re-samples. Effect sizes, f^2 were also calculated to assess the strength of influence that an exogenous latent construct exerts on an endogenous latent construct [46]. This study evaluated the model fit, including the path model's explanatory power, R^2, and predictive relevance, Q^2, using the PLSPredict procedure. The R^2 values indicate the proportion of variance in the endogenous variables explained by the exogenous constructs [48]. The Q^2 assesses how well the model can predict new observations, which is crucial for evaluating the model's capability to predict endogenous constructs outside the sample used for estimation. Model fit was assessed using the Standardized Root Mean Squared Residual (SRMR); values smaller than 0.10 may be considered acceptable [49]. Furthermore, a permutation analysis of measurement invariance assessment (MICOM) was conducted to determine whether the constructs were equally understood across two groups with different company ownerships. MICOM was evaluated using four criteria: configural invariance, compositional invariance, equality of composite means, and equality of composite variances. Insignificant *p*-values were the main criteria for these assessments. Finally, an MGA was performed to identify differences in path coefficients between the two ownership groups. To summarize the steps undertaken in this research, a simplified version of the methodology is depicted in Figure 2. This figure provides a clear and concise visual representation of the key phases and actions involved in the study.

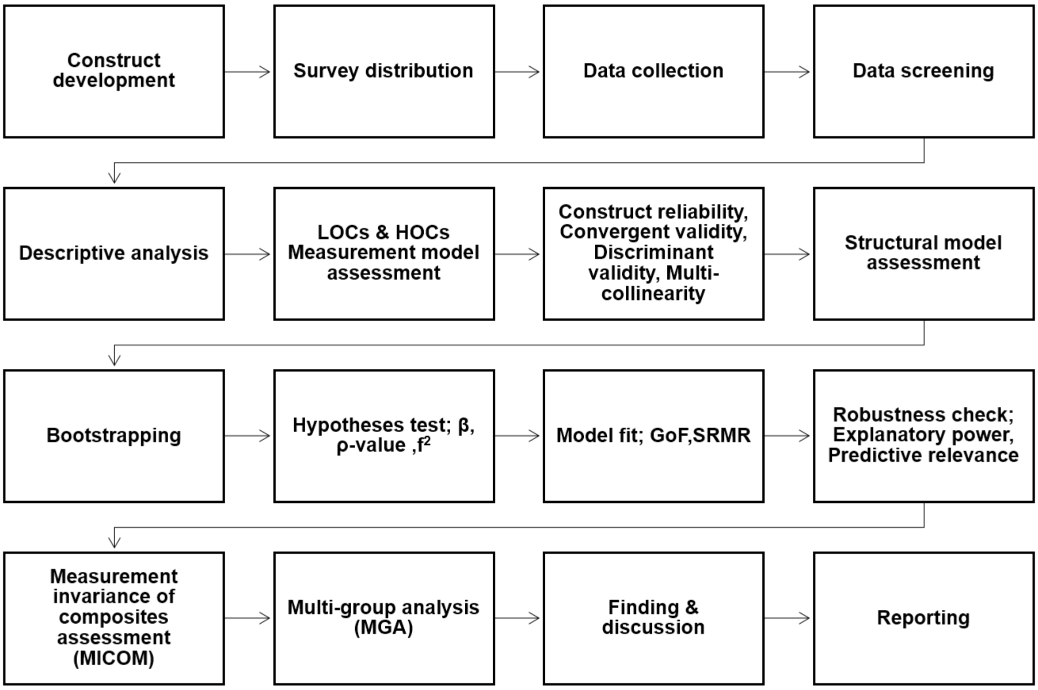

Figure 2. Research process

3. RESULTS AND DISCUSSION

A total of 296 completed questionnaires were received, yielding a response rate of 47.36%. After excluding missing values, outliers, and reluctant respondents, 276 responses were suitable for analysis. Of these respondents, 216 were male (78.26%) and 60 were female (21.74%). The median working experience ranged from 6 to 10 years, with most respondents having 1 to 5 years of quality management experience in WWTP. Regarding sectors, 182 respondents (65.94%) were affiliated with the manufacturing industry, while 94 (34.06%) represented agricultural, domestic WWTP, and other service sectors. The dataset also included 183 respondents (66.30%) from local WWTP ownerships and 93 respondents (33.70%) from MNCs that owned WWTPs. The subsequent section will provide detailed results and discuss the findings of the hypotheses.

3.1 Measurement Model Assessment

The measurement model assessment focuses on establishing construct reliability and validity using α and CR. Table 1 presents the construct reliability and convergent validity for both the ownership-specific and complete samples. The α and CR values for all constructs exceeded the recommended value of 0.7, ensuring good construct reliability. The AVE for all latent constructs was above 0.5, supporting convergent validity. The CR for the lower-order construct (LOC) was acceptable (> 0.5). Discriminant validity was confirmed using the HTMT criterion (see Tables 2 to 4). The HTMT values were below 0.90, indicating the robustness and adequacy of the measurement model. Additionally, the overall hypothesized model showed a Goodness of Fit of 0.583, and for both ownership types, it was 0.574 and 0.604, respectively, meeting the global criterion of 0.3 [50].

Table 1. Construct reliability and convergent validity

Items	Local			MNC			Complete		
	Alpha, α	CR	AVE	Alpha, α	CR	AVE	Alpha, α	CR	AVE
ECul	0.882	0.908	0.586	0.875	0.903	0.573	0.879	0.906	0.581
EEnv	0.882	0.909	0.589	0.881	0.908	0.585	0.883	0.909	0.589
ELnk	0.788	0.854	0.540	0.789	0.855	0.544	0.787	0.854	0.540
ERes	0.781	0.851	0.535	0.815	0.872	0.577	0.793	0.858	0.548
EStra	0.866	0.899	0.599	0.863	0.897	0.594	0.865	0.898	0.597
HRM	0.871	0.900	0.564	0.899	0.920	0.622	0.881	0.907	0.583
SPC	0.837	0.885	0.606	0.836	0.884	0.606	0.837	0.885	0.607
TPM	0.794	0.859	0.550	0.816	0.872	0.578	0.801	0.863	0.559
Eco_Perf	0.907	0.925	0.606	0.905	0.922	0.598	0.906	0.923	0.602
Env_Perf	0.876	0.902	0.537	0.917	0.932	0.633	0.892	0.914	0.570
Soc_Perf	0.904	0.923	0.600	0.924	0.938	0.657	0.912	0.929	0.620

Note: ECul: Culture enabler, EEnv: Environmental enabler, ELnk: Linkage enabler, ERes: Resource enabler, EStra: Strategic enabler, HRM: Human resource management, SPC: Statistical process control, TPM, Total productive maintenance, Eco_Perf: Economic performance, Env_Perf: Environmental performance, Soc_Perf: Social performance

Table 2. HTMT for a local company

	ECul	EEnv	ELnk	ERes	EStra	Eco_Perf	Env_Perf	HRM	SPC	Soc_Perf	TPM
ECul											
EEnv	0.589										
ELnk	0.594	0.549									
ERes	0.611	0.609	0.722								
EStra	0.617	0.650	0.587	0.574							
Eco_Perf	0.464	0.375	0.231	0.446	0.404						
Env_Perf	0.444	0.411	0.459	0.463	0.480	0.383					
HRM	0.589	0.469	0.475	0.496	0.506	0.540	0.423				
SPC	0.370	0.277	0.338	0.446	0.389	0.504	0.448	0.487			
Soc_Perf	0.518	0.475	0.459	0.492	0.497	0.545	0.612	0.568	0.506		
TPM	0.305	0.188	0.163	0.295	0.161	0.410	0.305	0.563	0.601	0.340	

Table 3. HTMT for MNC company

	ECul	EEnv	ELnk	ERes	EStra	Eco_Perf	Env_Perf	HRM	SPC	Soc_Perf	TPM
ECul											
EEnv	0.617										
ELnk	0.649	0.633									
ERes	0.732	0.722	0.782								
EStra	0.635	0.704	0.714	0.617							
Eco_Perf	0.276	0.210	0.276	0.376	0.255						
Env_Perf	0.430	0.327	0.370	0.410	0.357	0.334					
HRM	0.488	0.467	0.441	0.510	0.471	0.207	0.326				
SPC	0.405	0.310	0.633	0.523	0.408	0.465	0.323	0.665			
Soc_Perf	0.579	0.556	0.628	0.712	0.571	0.399	0.575	0.414	0.527		
TPM	0.354	0.238	0.394	0.320	0.167	0.367	0.292	0.607	0.706	0.200	

Table 4. HTMT for overall company

	ECul	EEnv	ELnk	ERes	EStra	Eco_Perf	Env_Perf	HRM	SPC	Soc_Perf	TPM
ECul											
EEnv	0.591										
ELnk	0.611	0.577									
ERes	0.654	0.649	0.748								
EStra	0.625	0.659	0.630	0.590							
Eco_Perf	0.396	0.290	0.244	0.417	0.338						
Env_Perf	0.440	0.371	0.419	0.442	0.433	0.358					
HRM	0.552	0.470	0.462	0.504	0.492	0.415	0.384				
SPC	0.374	0.267	0.434	0.472	0.389	0.489	0.398	0.547			
Soc_Perf	0.540	0.493	0.523	0.578	0.523	0.489	0.599	0.507	0.517		
TPM	0.323	0.197	0.233	0.303	0.149	0.393	0.296	0.580	0.637	0.273	

3.2 Validating Higher Order Constructs

LSS_En and Sus_Perf are higher-order reflective-formative constructs based on five LOCs (ECul, EEnv, ELnk, ERes, and EStra) and three LOCs (Eco_Perf, Env_Perf, and Soc_Perf) respectively. Several steps were undertaken to validate these higher-order constructs (HOCs). Firstly, multi-collinearity was assessed using the VIF. According to Hair et al. [46], no multi-collinearity issues were found, as all VIF values were less than 5 (see Table 5). Next, the statistical significance and relevance of outer weights were analyzed. In the local and complete datasets, EEnv and ELnk were found to be insignificant. Additionally, in the MNC dataset, all outer weight p-values for these LOCs were insignificant except for ELnk, ERes, and Soc_Perf. Furthermore, all outer loadings were required to be greater than 0.5, and this condition was met except for Eco_Perf (0.493) in the MNC dataset. However, the value is close to 0.5 [51]. Therefore, the HOCs were validated.

Table 5. Higher-order construct validation

		ECul	EEnv	ELnk	ERes	EStra	EcoPerf	EnvPerf	SocPerf
Local	VIF	1.769	1.836	1.737	1.782	1.912	1.368	1.469	1.727
	Outer Weight	0.467	0.112	-0.005	0.358	0.289	0.482	0.329	0.424
	p-value	0.000	**0.293**	**0.967**	0.001	0.007	0.000	0.000	0.000
	Outer Loading	0.871	0.717	0.639	0.797	0.793	0.818	0.740	0.854
	p-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
MNC	VIF	1.934	2.114	2.052	2.295	2.170	1.186	1.423	1.517
	Outer Weight	0.238	0.021	0.326	0.442	0.162	0.124	0.126	0.872
	p-value	**0.114**	**0.892**	0.043	0.007	**0.292**	**0.460**	**0.427**	0.000
	Outer Loading	0.797	0.707	0.847	0.898	0.751	**0.493**	0.630	0.986
	p-value	0.000	0.000	0.000	0.000	0.000	0.004	0.000	0.000
Complete	VIF	1.807	1.882	1.828	1.921	1.963	1.289	1.449	1.637
	Outer Weight	0.405	0.067	0.116	0.382	0.255	0.356	0.289	0.585
	p-value	0.000	**0.449**	**0.237**	0.000	0.006	0.000	0.001	0.000
	Outer Loading	0.857	0.704	0.727	0.842	0.782	0.724	0.730	0.909
	p-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

3.3 Structural Model Assessment

As part of the structural model assessment, the first step is to check for multi-collinearity HOCs using VIF. VIF values for the inner model range from 1.000 to 1.426, below the recommended threshold of 5 [46], indicating no multi-collinearity issues for both the ownership sub-samples and the overall sample. Next, the bootstrapping results for the relationships between company ownership groups are presented based on the hypotheses. The results in Table 6 show that the local ownership and complete samples support all hypotheses. However, in the MNCs group, H3; (LP→Sus_Perf, $\beta = 0.129$, $t = 1.047$, $p = 0.295$) for the direct relationship and H4; (LSS_En→LP→Sus_Perf, $\beta = 0.071$, $t = 0.976$, $p = 0.329$) for mediation are both insignificant. Next, this study assessed the effect sizes of f^2 for direct effects and statistic upsilon, υ for mediation effects. It determines whether an external underlying concept has a weak, moderate, or significant influence on an internal underlying concept. Hair et al. [45] propose examining changes in the R^2 value, while Cohen [52] suggests using f^2 values of 0.35 (large effects), 0.15 (medium effects), and 0.02 (small effects) as guidelines for measuring direct effects. Following these guidelines, Table 3 presents the results of f^2, indicating medium to large effects on the direct relationships within the entire dataset, but small effect sizes of 0.022 on the H3, LP implementation to Sus_Perf relationship in MNCs. In addition, the MNCs group indicates higher f^2 in H1 compared to the local-owned companies, with $f^2 = 0.491$, versus local companies (0.244), respectively, suggesting that MNCs agreements, when prioritizing the LSS_En, can enhance the WWTP Sus_Perf. Moreover, both ownership groups argue that H2 has a large effect size with 0.421 and 0.426, respectively, indicating that the LSS_En is the significant factor for LP implementation.

Regarding the effect size for mediation relationships, Cohen [52], as cited in Ogbeibu et al. [53], recommends using upsilon, υ values of 0.175 (significant effect), 0.075 (medium effect), and 0.010 (small effect) as guidelines. Table 3 shows small effect sizes for the mediation relationship: 0.052 in the local dataset, 0.031 in the complete dataset, and 0.005 for MNCs. These findings suggest that although LP positively mediates the relationship in Malaysian and overall companies, the small effect sizes indicate weak relationships in the structural model. Hence, more practical LPs are needed in future research. Subsequently, the model's explanatory power was assessed. The R^2 values ranged from 0.287 to 0.524 across all samples in the study. These R^2 values are classified as moderate explanatory power [48]. Q^2 values were used to evaluate predictive relevance. The Q^2 values for the endogenous constructs ranged from 0.240 to 0.385, considered medium to large prediction capability [48]. Moreover, an SRMR value between 0.064 to 0.070, below 0.10, indicates that the model fits well [49].

Table 6. Hypotheses testing results

Group	Criterion	Hypotheses				LP	Sus_Perf
		H1: LSS_En → Sus_Perf	H2: LSS_En → LP	H3: LP → Sus_Perf	H4: LSS_En → LP → Sus_perf		
Local	β	0.406	0.544	0.418	0.228		
	t	5.629	10.541	5.903	4.719		
	p	0.001	0.001	0.001	0.001		
	Results	√*	√*	√*	√*		
	f^2	0.244	0.421	0.259	0.052		
	R^2					0.296	0.524
	Q^2					0.269	0.355
MNC	β	0.608	0.546	0.129	0.071		
	t	6.025	7.130	1.047	0.976		
	p	0.001	0.001	0.295	0.329		
	Results	√*	√*	X	X		
	f^2	0.491	0.426	0.022	0.005		
	R^2					0.299	0.472
	Q^2					0.240	0.385
Complete	β	0.455	0.536	0.330	0.177		
	t	7.787	12.241	5.463	4.660		
	p	0.001	0.001	0.001	0.001		
	Results	√*	√*	√*	√*		
	f^2	0.281	0.403	0.148	0.031		
	R^2					0.287	0.476
	Q^2					0.270	0.369

Note: *Relationships significant at $p < 0.05$, β: Beta coefficient, *t*: t-statistics, *p*: Probability value, √: Supported, X: Not supported.

3.4 Multi-group Analysis

Before conducting the Multi-group Analysis (MGA), the MICOM was evaluated using four criteria: configural invariance, compositional invariance, equality of composite mean, and equality of composite variance. Insignificant *p*-values are the main criteria for establishing these assessments. For the last three criteria, the *p*-value > 0.05 indicated that the MICOM was established, allowing to proceed to the full MGA. In the final part of the research, after performing MICOM, the significant differences between local and MNC companies concerning the effects of the following hypotheses H1; LSS_En on Sus_Perf, H2; LSS_En on LP, H3; LP on Sus_Perf, and the mediating role of H4; LP between LSS_En and Sus_Perf were examined. The findings revealed that the differences were insignificant except for H3, with $p > 0.05$. However, the impact of LP implementation on the Sus_Perf was stronger in locally owned companies than in MNCs, with difference of 0.289 and $p = 0.043$. The results of the MGA are summarized in Table 7.

Table 7. Multi-group analysis results

Relationships	Difference (Local - MNC)	*p*-value
Direct relationships		
H1: LSS_En → Sus_Perf	-0.202	0.110
H2: LSS_En→ LP	-0.002	0.964
H3: LP → Sus_Perf	0.289	0.043*
Mediation relationship		
H4: LSS_En → LP → Sus_Perf	0.157	0.075

Note: *The difference are significant in the relationship between the two groups of company ownership ($p < 0.05$).

4. CONCLUSIONS

The research investigates the impact of LSS_En on Sus_Perf, mediated by HRM, SPC, and TPM, the key LP tools in Malaysian WWTPs, addressing the main research objective through four hypotheses. The findings indicate a positive and significant effect in direct (H1, H2, H3) and mediated (H4) relationships in Malaysian-owned companies and across the complete dataset. These results support the idea that combining lean and green initiatives can enhance company and sustainability performance. However, in MNCs, while LSS_En's positively influences Sus_Perf (H1) and LSS_En's positively affects LP (H2), the direct relationship between LP on Sus_Perf (H3), as well as LP's mediating role in H4, were insignificant. Although LSS_En positively impacts Sus_Perf, the level of LP implementation does not sufficiently support sustainability performance in MNCs. Furthermore, this study reveals a medium to large direct effect size (f^2) in an overall significant relationship, indicating that LSS_En significantly enhances Sus_Perf. LSS_En also facilitates LP implementation, improving the Sus_Perf in Malaysian and complete datasets. However, the effect size (f^2) in MNCs is low, suggesting insignificant findings regarding how LP implementation promotes Sus_Perf. The study further identifies LP implementation as enhancing sustainable performance through LSS_En in local and overall samples, although the effect size is relatively weak. Additional exploration is necessary to comprehend why LP's mediating role in promoting sustainable performance is insignificant, particularly considering the diverse management styles of MNCs from the USA, Europe, and Asia-based companies.

Moreover, the MGA findings confirm that local companies excel in LP implementation to promote sustainable performance in WWTP operations, compared to the notable differences observed in H3 among MNCs. Additionally, this study establishes moderate explanatory power (Q^2) and acceptable predictive capability for future research. This study offers valuable insights and practical implications for various stakeholders. Top management should integrate LSS_En to promote Sus_Perf by prioritizing the LSS projects with meaningful impact rather than implementing a generic continuous improvement approach in WWTPs, which can lead to ownership issues. Effective teamwork, communication, and scheduling through employee retention, empowerment, and knowledge sharing will foster a sustainable organizational culture and ethical practices. However, this study has limitations. It employed a cross-sectional research design, highlighting the need for longitudinal studies to track the long-term effects and dynamic implementation of LSS. As empirical research on the relationships between LSS_En, LP, and Sus_Perf is relatively new, it sheds light on their specific combination in WWTP operations. Moreover, combining MGA analysis provides insights into this domain, highlighting key areas for future LSS implementation in Malaysia's environmental control sectors.

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CONFLICT OF INTEREST

The authors declare that they do not have any conflict of interest.

AUTHORS CONTRIBUTION

E. Mohamad (Supervision; Conceptualization; Methodology; Writing – original draft)

A. Ishak (Data curation; Formal analysis; Writing – original draft)

H. Arep (Supervision; Formal analysis; Writing – review and editing)

AVAILABILITY OF DATA AND MATERIALS

The data supporting this study's findings are available on request from the corresponding author.

ETHICS STATEMENT

Not applicable

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