

Confirmatory factor analysis for the implementation of Green Lean Six Sigma (GLSS) in Malaysia's wastewater treatment industry

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ABSTRACT

This study investigates the critical enablers influencing the implementation of Green Lean Six Sigma (GLSS) in Malaysia's wastewater treatment industry. Through an extensive literature review and insights from the industry, 30 distinct enablers were identified and categorized based on their characteristics within wastewater treatment plant (WWTP) organizations, aimed at ensuring successful GLSS execution. Structural equation modelling was employed to validate the research model, utilizing data from 296 certified professionals in Malaysia. The analysis revealed five significant enablers, indicating moderate to high levels of GLSS adoption within the industry, with the 'strategic' and 'resource' enablers emerging as particularly influential factors. Subsequent confirmatory factor analysis further affirmed the validity and reliability of these enablers. Moreover, the findings demonstrated both convergent and discriminant validity, reinforcing the efficacy of these factors in measuring GLSS implementation in Malaysian WWTPs. The study highlights the critical importance of strategic planning and resource allocation while emphasizing the need to address cultural and environmental factors for successful GLSS adoption in the industry. However, enablers based on linkages, particularly those pertaining to supplier relationships and customer satisfaction, garnered the least consensus among respondents, indicating areas necessitating further attention and improvement.

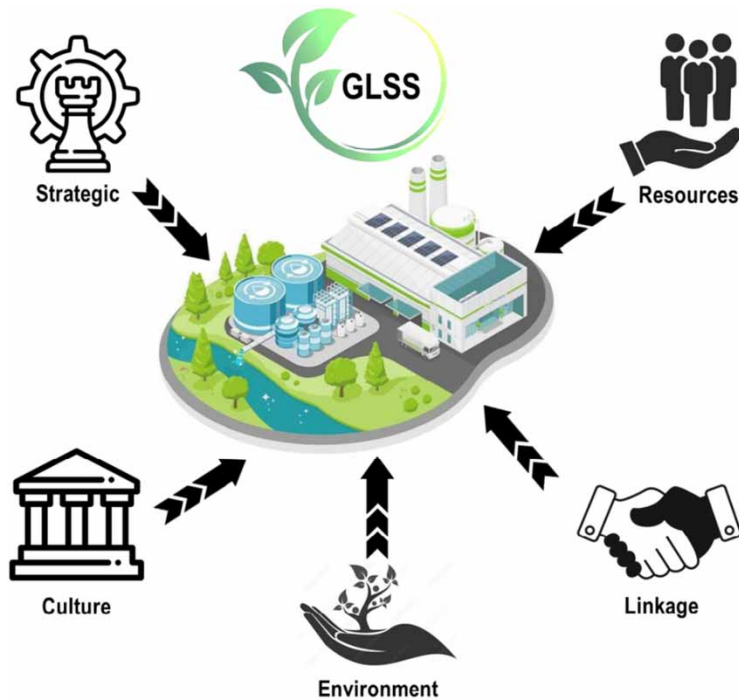
Key words: Critical enablers, Green manufacturing, Lean Six Sigma, Structural equation modelling, Wastewater treatment

HIGHLIGHTS

- This study represents the first integrated CFA model combining the concepts of green manufacturing to examine the sustainability of wastewater treatment plant (WWTP) operations.
- The research underscores the novelty of its theoretical and managerial implications, prompting WWTP professionals to reconsider their current operational management strategies to facilitate improved outcomes in treated quality, nutrient recovery, and energy conservation.

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GRAPHICAL ABSTRACT



1. INTRODUCTION

The progression of modernization in manufacturing, driven by the increasing global recognition of environmental risks and the pursuit of enhanced efficiency, has evolved from traditional substitution focus to lean manufacturing, which minimizes waste, and further advanced to green manufacturing guided by the principles of reduce, reuse, and recycle (3Rs) (Sagnak & Kazancoglu, 2016). Enterprises have proactively developed cleaner manufacturing processes and environmentally friendly products. However, numerous industrial activities significantly impact the environment and society assigned to excessive resource consumption, generation of hazardous wastes, and emissions (Parmar & Desai, 2020).

Wastewater, encompassing various types such as sewage, domestic, storm run-off, agricultural, and industrial wastewater (Ishak *et al.*, 2022a), constitutes a notable component of industrial waste. According to the United Nations, approximately 1.6 billion people face economic water shortage, and two-thirds of the world's population experience water scarcity for at least 1 month per year (Christou *et al.*, 2024). This scarcity issue is exacerbated by the fact that around 97% of Malaysia's total raw water supply is derived from freshwater bodies, including lakes, rivers, and tributaries (Kozaki *et al.*, 2016). The problem of water pollution, which has historical roots in urbanization and modernization, continues to escalate in severity (Ismail *et al.*, 2020). Furthermore, industrial effluents pose significant harm to ecosystems. When poorly treated or directly released into sewers, they pollute groundwater and water bodies, adversely affecting animals and aquatic life. Inadequate treatment also leads to air and land pollution, which negatively impacts soil quality. Disposal of industrial wastewater poses risks to crops and potentially disrupts the food chain, contributing to the spread of waterborne diseases (Von Sperling *et al.*, 2020).

Wastewater treatment plants (WWTPs) face multifaceted challenges, including influent fluctuations, reactor dynamics, pollutant origins, process variability, mechanical anomalies, and human proficiency. Equipment malfunction, including damage, breakdowns, and unforeseen downtime, poses a substantial concern in environmental control, disrupting treatment processes and compromising the quality of treated wastewater (Ishak *et al.*, 2022b). Remedial techniques have emerged to identify operational shortcomings and rectify instability and inadequacies in treatment methodologies. Scholars have developed approaches combining green and lean concepts (Siegel *et al.*, 2019) to minimize not only waste production but also 'green waste' (Caiado *et al.*, 2018), defined by the United States Environmental Protection Agency (US EPA) as avoidable resource consumption or substance release detrimental to humans and the environment (United States Environmental Protection Agency, 2007). Optimizing the usage of energy, water, chemicals, materials, or transportation can profoundly impact ecosystems.

Recognizing the limitations of green and lean as independent strategies and as an integrated paradigm, Green Lean Six Sigma (GLSS) emerges as a pioneering environmental developmental agenda, transcending these constraints and enhancing the effectiveness of green lean initiatives (Shokri & Li, 2020). This integration draws strength not only from the intrinsic cohesion of lean principles and tools common in both approaches but also from their ostensibly shared attributes (Rahman & James, 2019). Although numerous studies have showcased the effectiveness of this integration, further cutting-edge research, particularly empirical inquiries offering structured guidelines for applying GLSS across diverse domains, is imperative (Gholami *et al.*, 2021). Precisely defining this concept necessitates the systematic consolidation of available knowledge regarding this GLSS initiative.

Despite its recognized potential in the manufacturing industry, practitioners exhibit caution in GLSS adoption (Farrukh *et al.*, 2021). Consequently, there is a research imperative to scrutinize the factors facilitating GLSS implementation in WWTPs. Notably, no prior studies have explicitly and systematically addressed a comprehensive model of GLSS in WWTP operations, indicating a need for a unified model. Critical tasks involve organizing existing GLSS insights and identifying impediments, particularly within Malaysian WWTPs where specific GLSS enablers remain unexplored. This study aims to augment current knowledge and expedite GLSS implementation by (1) delineating key factors enabling GLSS implementation, (2) constructing a structured framework for GLSS integration in the Malaysian WWTP sector, and (3) empirically investigating the GLSS enabler's model in WWTP operations using structural equation modelling (SEM).

2. LITERATURE REVIEW

In the literature, enablers are recognized as key factors that significantly influence the alignment of quality management with organizational goals and performance (Yadav & Desai, 2017). Various researchers have explored enablers within the realm of GLSS. For instance, Kumar *et al.* (2015) conducted a study identifying the 44 GLSS enablers that impact the sustainability performance of Indian enterprises. Singh *et al.* (2021) employed a hybrid Best-Worst method (BWM), analytic hierarchy process (AHP), and analytic network process (ANP) approach to categorize five types of GLSS enablers, including strategic, environmental, cultural, resource, and linkage-based enablers.

Strategic enablers, propelled by top management's commitment, serve as catalysts for GLSS by promoting innovation (Kaswan & Rathi, 2020a), resource allocation, and employee motivation (Kaswan & Rathi, 2019). Their adept decision-making skills contribute to sustainability and organizational improvements (Hariyani & Mishra, 2022; Shokri *et al.*, 2022). Additionally, effective project leadership, encompassing diverse roles, fosters transparency, cooperation, and alignment with business objectives, leading to significant outcomes (Ershadi *et al.*, 2021; Mishra, 2022). Furthermore, integrating rewards for employees encourages heightened engagement with

human resources, enhancing eco-friendly results, thus reinforcing fairness and loyalty (Parmar & Desai, 2020; Letchumanan *et al.*, 2022).

Organizational readiness necessitates competent individuals and supportive structures (Kaswan & Rathi, 2020b), which are important for sustainable GLSS adoption (Letchumanan *et al.*, 2022; Mishra, 2022). Moreover, robust performance measurement and reliable results tracking are crucial (Pandey *et al.*, 2018), especially in dynamic WWTP operations, guiding decision-making and error-proofing through feedback mechanisms (Singh *et al.*, 2021). Additionally, a resilient data collection system facilitates structured information retrieval, enabling comparisons across WWTP stages and the supply chain. Monitoring and controlling using information tools are central for effective management in GLSS contexts (Hariyani & Mishra, 2022).

Transitioning to green practices in manufacturing (Farrukh *et al.*, 2021), including WWTP operations, facilitates the reduction of energy use, CO₂ emissions, and waste generation, thereby positively impacting environmental performance (Abdul-Rashid *et al.*, 2017; Kaswan & Rathi, 2019; Farrukh *et al.*, 2022). Environmental-based enablers, such as emphasizing biodegradable packaging and supplier adherence (Dieste *et al.*, 2019), for instance, utilizing materials like biodegradable options and lightweight, flexible packaging, help minimize costs and environmental emissions (Farrukh *et al.*, 2023a; Rathi *et al.*, 2023). In many cases, environmental initiatives rely on government regulations to support GLSS through incentives like subsidies, influencing top management, and enhancing organizational capabilities (Hariyani & Mishra, 2022).

Additionally, eco-design prioritizes minimizing environmental footprints (Parmar & Desai, 2020), aligning with WWTP goals (Ishak *et al.*, 2022b), which not only focus on treating wastewater to acceptable standards but also optimize energy recovery and nutrient recovery sources. Furthermore, the impact of logistics and transportation on emissions underscores the importance of green methods (Pandey *et al.*, 2018). Similarly, WWTP practices optimize chemical use and effluent transport, promoting sustainability (Rimantho & Nugraha, 2020). Moreover, the environmental management system (EMS) integrates various environmental activities (Shokri *et al.*, 2022), enhancing facility sustainability (Singh & Rathi, 2022, 2023). Additionally, stakeholder pressure emphasizes demands for eco-conscious practices (Gandhi *et al.*, 2018; Parmar & Desai, 2019), driven by regulations and consumer preferences for green initiatives (Nagadi, 2022) and sustainable performance (Yadav *et al.*, 2023a, b).

In culture-based enablers, team selection holds paramount importance (Kumar *et al.*, 2015), leveraging diverse skills and experiences as valuable assets (Singh *et al.*, 2021). For example, talented WWTP employees enhance treatment efficiency (Letchumanan *et al.*, 2022; Mishra, 2022), emphasizing unified effort and effective communication channels (Pandey *et al.*, 2018). Similarly, GLSS emphasizes teamwork for sustainable improvements (Kaswan & Rathi, 2020a), supported by effective communication (Hussain, *et al.*, 2023; Hariyani & Mishra, 2024) and inter-departmental exchanges (Singh *et al.*, 2021; Hariyani *et al.*, 2023; Hussain *et al.*, 2023).

Moreover, efficient scheduling (Yadav *et al.*, 2021; Shokri *et al.*, 2022) aids environmental sustainability (Letchumanan *et al.*, 2022). Similarly, motivating employees (Singh *et al.*, 2021; Mishra, 2022) and cross-departmental sharing enhances efficiency (Hussain *et al.*, 2023). Likewise, sharing success stories facilitates learning (Mishra, 2022), emphasizing factors such as management commitment and training (Singh *et al.*, 2021). Ultimately, GLSS culture values sustainability (Gandhi *et al.*, 2018), ethics (Kaswan & Rathi, 2019), and profitability (Kaswan & Rathi, 2020a; Hariyani & Mishra, 2023; Rathi *et al.*, 2023). Therefore, cooperative WWTP environments focus on quality, efficiency, and participative cultures (Letchumanan *et al.*, 2022; Mishra, 2022) for successful GLSS implementation (Hussain *et al.*, 2023).

The GLSS methodology, integrating Lean Six Sigma (LSS; Yadav *et al.*, 2021) and flow cost accounting, addresses inefficiencies (Kaswan & Rathi, 2019). Emphasis is placed on understanding for successful adoption (Hussain *et al.*, 2023). Project selection aligns with sustainability (Parmar & Desai, 2019), utilizing Lean tools such as fishbone diagrams for prioritizing improvements and resource allocation to enhance continuous

improvement projects in organizations (Letchumanan *et al.*, 2022; Hussain *et al.*, 2023). Mastery of project selection and prioritization skills (Singh *et al.*, 2021; Rathi *et al.*, 2023), along with effective training, is crucial (Hariyani & Mishra, 2024) for GLSS success (Mishra, 2022).

Careful financial planning (Hussain *et al.*, 2023) ensures effective resource allocation for technology upgrading (Kumar *et al.*, 2015; Singh *et al.*, 2021), particularly in WWTP operations, which require capacity and efficiency commensurate with process enlargement. Periodical staff training improves skill sets, employability, team spirit, and organizational cohesiveness (Shokri *et al.*, 2022). Continual assessment of financial benefits (Pandey *et al.*, 2018; Yadav *et al.*, 2021) and early involvement of finance departments are essential (Letchumanan *et al.*, 2022; Shokri *et al.*, 2022; Hussain *et al.*, 2023) for effective resource management. In WWTP operations, selecting eco-friendly polymers, exemplified by involving financial perspectives for cost-effective measures, helps reduce long-term treatment expenses and environmental impact (Singh *et al.*, 2021; Mohan *et al.*, 2022).

Supplier engagement in GLSS promotes innovation and quality improvement (Kaswan & Rathi, 2020b; Parmar & Desai, 2020). Ensuring reliable suppliers is crucial for the timely delivery of chemicals, nutrient additives, and mechanical equipment, which are vital for WWTP operations' performance and waste management (Digalwar *et al.*, 2020; Singh *et al.*, 2021), including bio-sludge and solid waste disposal. Moreover, customer satisfaction in WWTP operations depends on adaptable processes, legal compliance, cost control, and pollution prevention (Kaswan & Rathi, 2020b). Accurate predictions and digital advancements enhance customer satisfaction and engagement (Singh *et al.*, 2021). Customer involvement is integral to GLSS success (Pandey *et al.*, 2018), prioritizing satisfaction through feedback and database utilization (Ershadi *et al.*, 2021).

Meeting customer demand entails maintaining stable treated wastewater quality and cost-effective plant operations (Singh *et al.*, 2021). Strong customer-supplier relationships (Pandey *et al.*, 2018; Letchumanan *et al.*, 2022) focusing on sustainability, optimizing outcomes, and minimizing waste (Hariyani & Mishra, 2024) contribute to efficient treatment processes. Integrating GLSS into strategy enhances sustainability (Kaswan & Rathi, 2020b; Hussain *et al.*, 2023), fostering staff responsibility (Farrukh *et al.*, 2019) and collaboration (Farrukh *et al.*, 2021) in high-risk operations such as WWTP.

In conclusion, this literature review explores essential GLSS enablers for sustainable operations, aiming to underscore the importance of holistic assessments of these enablers to optimize their impact on operational sustainability and to further enhance Malaysia's wastewater treatment practices. Understanding the interplay among these enablers will facilitate the development of improved strategies and implementation methodologies for sustainable wastewater management.

3. METHODOLOGY

This study constitutes exploratory research, focusing on an unexplored area within Malaysian WWTPs. It adopts a descriptive and analytical approach towards its exploratory aim, comprising two distinct phases. The first phase entails a comprehensive review of existing literature on GLSS enablers. Following this, an analytical method is formulated to conclude the research process. These steps are further elaborated upon in the subsequent sections.

To begin, following Yadav *et al.* (2023a, b) scholarly papers were gathered from reputable databases including Elsevier, Springer, Science Direct, Taylor & Francis, Emerald, Sage, and among others. A comprehensive literature review and on-site visits to actual WWTPs enabled the compilation of a list of key factors that impact the implementation of GLSS in Malaysian WWTP scenarios. Articles focusing on enablers, drivers, and critical success factors (CSFs) related to GLSS were meticulously examined, both theoretically and empirically, to inform this compilation.

Next, in the classification of GLSS enablers, experts' insights and exploratory factor analysis (EFA) have been utilized. EFA serves to gauge the identified variables and unveil the underlying relationships among them. This

method yields two interconnected outcomes: data summarization and reduction. Through data summarization, EFA identifies core dimensions that succinctly encapsulate the data, condensing numerous individual variables into a smaller set of concepts. Data reduction builds on this by assigning a numerical value (factor score) to each dimension (factor), replacing the original values. Many researchers find EFA valuable for uncovering patterns among variables or as a means of streamlining data. This analytical approach encompasses three primary components, elaborated upon in the following sections.

The EFA design focused on two critical queries: identifying key GLSS enablers and determining an optimal sample size. A comprehensive literature review and collaboration with certified LSS Belts, National Registration of Certified Environmental Professional experts in WWTP operations, and a GLSS academician led to refining 30 enablers. [Hair et al. \(2019\)](#) recommends at least 50 observations for EFA, while [Habidin & Yusof \(2013\)](#) used 161 observations to identify the LSS CSFs model in the Malaysian automotive sector. Employing non-probabilistic convenience sampling, 296 responses were collected from local WWTP professionals between February and May 2023. A five-point Likert scale measured perceptions of agreement (strongly disagree – 1 to strongly agree – 5) regarding GLSS enabler importance, validated by another five WWTP experts. A pilot study ensured questionnaire clarity and relevance. Data collection targeted diverse viewpoints from technicians, engineers, executives, and managers involved in various aspects of WWTP in industrial operations. Subsequent analysis choices, like factor extraction methods and matrices, will critically shape the understanding of the identified enablers' underlying structure. These decisions are crucial for interpreting the study's outcomes effectively.

Again, [Hair et al. \(2019\)](#) advocates using principal component analysis (PCA) with varimax rotation due to its ability to consider total variance and highlight factors with less unique variance. This method maximizes variance in factor loadings, simplifies fundamental structures, and aids in factor division ([Hashemi et al., 2022](#)). Employing IBM SPSS version 27, this study used Bartlett's test of sphericity (BTS) and Kaiser–Meyer–Olkin (KMO) measure to assess data suitability. Acceptable EFA standards include BTS at 0.05 significance and KMO between 0 and 1, with 0.5 as minimal adequacy ([de Freitas et al., 2017](#)). Criteria for determining factor numbers include variance contribution (>20%), eigenvalues (>1), and the Scree test ([Hair et al., 2019](#)), while [Letchumanan et al. \(2021\)](#) suggest considering factor loadings >0.5. Internal consistency, evaluated by Cronbach's α (>0.6), ensures reliability in the exploratory survey.

Finally, SEM, increasingly popular in operations management empirical studies ([Habidin & Yusof, 2013](#)), combines regression and factor analysis to explore relationships between observed and latent variables. It comprises two stages: EFA, exploring links between observed and unobserved variables, and confirmatory factor analysis (CFA), confirming and validating models as explained previously by EFA. While CFA, conducted in Analysis of Moment Structure (AMOS) version 24, validates the measured and structural models. This method enables a comprehensive evaluation of complex relationships between variables in this study.

4. RESULTS AND DISCUSSION

The study assessed the reliability and validity of GLSS enablers through an EFA. Initially, 30 enablers were identified from an extensive literature review and industrial visit. These enablers were distinct in their characteristics and application within WWTP organizations to ensure the successful execution of GLSS. They were categorized based on their traits, employing both fundamental and statistical methods. Building on prior work by [Singh et al. \(2021\)](#), EFA was conducted to unveil the structure of GLSS using these 30 enablers, as outlined in [Table 1](#).

PCA was employed to evaluate responses gathered from 296 experts working in various Malaysian WWTPs. This insight from experts is crucial as it provides decision-makers with a comprehensive understanding of a significant stakeholder group. The analysis revealed a high overall reliability coefficient (α) of 0.969, which is considered suitable ([Hair et al., 2019](#)). Moreover, the KMO measure surpassed the threshold of 0.7 at 0.968,

Table 1 | Total variance, eigenvalues, and reliability coefficients of the structured factors.

Total variance explained ^a		Factor ^{b,d}				
		1. Stra	2. Env	3. Cul	4. Res	5. Lnk
Initial eigenvalues	Total	15.998	1.606	1.456	1.092	1.047
	Variance (%)	53.325	5.354	4.855	3.641	3.490
	Cumulative (%)	53.325	58.679	63.534	67.175	70.666
Rotation sums of squared loadings	Total	4.988	4.430	4.409	4.010	3.363
	Variance (%)	16.628	14.766	14.695	13.365	11.212
	Cumulative (%)	16.628	31.393	46.089	59.454	70.666
Cronbach's alpha (α) ^c		0.924	0.939	0.895	0.866	0.924

^aExtraction method: PCA.

^bRotation has been performed by the Varimax method in eight iterations.

^cOverall reliability = 0.969.

^dKMO = 0.968. BTS is significant at $p < 0.001$.

indicating the adequacy of the data for PCA. Similarly, the BTS was significant ($p < 0.001$), affirming sufficient correlation among the items to proceed with the analysis.

The EFA identified five factors among the 30 GLSS items, explaining 70.666% of the total variance. None of the enabler items were suggested for exclusion. The determination of the total factor number for extraction was based on the widely used criteria, including the proportion of contribution to total variance, eigenvalues, and the Scree plot. The Scree plot indicated a clear drop and then stabilization at five factors, depicted in Figure 1. Additionally, the reliability measure of GLSS using Cronbach's α ranged from 0.866 to 0.939, where values equal to or greater than 0.60 are indicative of reliability (Abu *et al.*, 2019). Each factor exhibited a Cronbach's α value above 0.70, all factors were deemed reliable for the research. Consequently, all 30 initial enablers were retained as they displayed factor loadings >0.5 , as detailed in Table 2.

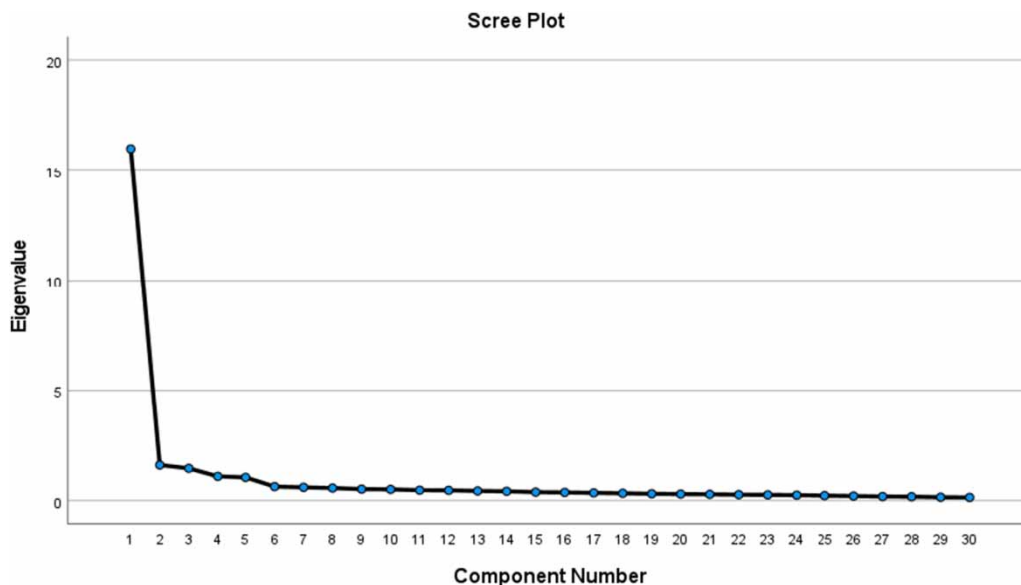
**Fig. 1** | Scree plot test.

Table 2 | EFA structure of GLSS enablers.

Enablers	Code	Comm ^a	Factors					References
			1	2	3	4	5	
Top management commitment	EStra1	0.694	0.733					Kumar <i>et al.</i> (2015), Kaswan & Rathi (2019, 2020b), Singh <i>et al.</i> (2021), Shokri <i>et al.</i> (2022), and Hariyani & Mishra (2022)
Effective project leadership	EStra2	0.778	0.717					Kumar <i>et al.</i> (2015), Ershadi <i>et al.</i> (2021), Singh <i>et al.</i> (2021), Hariyani & Mishra (2022), and Mishra (2022)
Rewards and incentives to employees	EStra3	0.698	0.690					Kumar <i>et al.</i> (2015), Parmar & Desai (2020), Singh <i>et al.</i> (2021), Ershadi <i>et al.</i> (2021), and Letchumanan <i>et al.</i> (2022)
Supportive organizational infrastructure	EStra4	0.755	0.675					Kumar <i>et al.</i> (2015), Kaswan & Rathi (2020a), Mishra (2022), and Letchumanan <i>et al.</i> (2022)
Performance measurement system	EStra5	0.763	0.719					Kumar <i>et al.</i> (2015), Pandey <i>et al.</i> (2018), Singh <i>et al.</i> (2021), Ershadi <i>et al.</i> (2021), and Letchumanan <i>et al.</i> (2022)
Consistent and accurate data collection	EStra6	0.736	0.668					Kumar <i>et al.</i> (2015), Ershadi <i>et al.</i> (2021), Hariyani & Mishra (2022), Letchumanan <i>et al.</i> (2022), and Hariyani & Mishra (2024)
Carbon reduction initiatives	EEnv1	0.716		0.592				Abdul-Rashid <i>et al.</i> (2017), Kaswan & Rathi (2019), Farrukh <i>et al.</i> (2021, 2022), and Singh <i>et al.</i> (2021)
Eco-packaging	EEnv2	0.745		0.726				Dieste <i>et al.</i> (2019), Farrukh <i>et al.</i> (2019, 2023a, b), and Rathi <i>et al.</i> (2023)
Incentives for eco-products	EEnv3	0.662		0.637				Kumar <i>et al.</i> (2015), Abdul-Rashid <i>et al.</i> (2017), Singh <i>et al.</i> (2021), and Farrukh <i>et al.</i> (2022)
Eco-design practices	EEnv4	0.790		0.760				Kumar <i>et al.</i> (2015), Farrukh <i>et al.</i> (2019), Singh <i>et al.</i> (2021), and Letchumanan <i>et al.</i> (2022)
Eco-transportation practices	EEnv5	0.817		0.791				Kumar <i>et al.</i> (2015), Pandey <i>et al.</i> (2018), Singh <i>et al.</i> (2021), and Letchumanan <i>et al.</i> (2022)
Green operational practices	EEnv6	0.752		0.675				Singh <i>et al.</i> (2021), Shokri <i>et al.</i> (2022), and Singh & Rathi (2023)
Market demand for eco-products	EEnv7	0.720		0.682				Kumar <i>et al.</i> (2015), Gandhi <i>et al.</i> (2018), Parmar & Desai (2019), Nagadi (2022), and Yadav <i>et al.</i> (2023a, b)
Select and retention of employees	ECul1	0.621			0.636			Kumar <i>et al.</i> (2015), Singh <i>et al.</i> (2021), Mishra (2022), and Letchumanan <i>et al.</i> (2022)
Teamwork	ECul2	0.643			0.659			Pandey <i>et al.</i> (2018), Kaswan & Rathi (2019, 2020a), Singh <i>et al.</i> (2021),

(Continued.)

Table 2 | Continued

Enablers	Code	Comm ^a	Factors					References
			1	2	3	4	5	
Effective communication	ECul3	0.639			0.629			Hariyani & Mishra, (2024), and Hussain <i>et al.</i> (2023)
Effective scheduling	ECul4	0.631			0.602			Kumar <i>et al.</i> (2015), Singh <i>et al.</i> (2021), Letchumanan <i>et al.</i> (2022), Hariyani & Mishra, (2024), and Hussain <i>et al.</i> (2023)
Empowering employees	ECul5	0.603			0.624			Kumar <i>et al.</i> (2015), Pandey <i>et al.</i> (2018), Singh <i>et al.</i> (2021), Shokri <i>et al.</i> (2022), and Mishra (2022)
Sharing success stories	ECul6	0.672			0.709			Yadav & Desai (2017), Singh <i>et al.</i> (2021), Mishra (2022), and Hussain <i>et al.</i> (2023)
Organizational culture and ethic	ECul7	0.615			0.641			Kumar <i>et al.</i> (2015), Gandhi <i>et al.</i> (2018), Kaswan & Rathi (2019), Mishra (2022), Letchumanan <i>et al.</i> (2022), and Hariyani & Mishra (2023)
Understand GLSS methodology	ERes1	0.724				0.705		Kumar <i>et al.</i> (2015), Kaswan & Rathi (2019), Singh <i>et al.</i> (2021), Yadav <i>et al.</i> (2021), and Hussain <i>et al.</i> (2023)
Project selection and prioritization	ERes2	0.611				0.597		Kumar <i>et al.</i> (2015), Parmar & Desai (2019), Singh <i>et al.</i> (2021), Letchumanan <i>et al.</i> (2022), and Hussain <i>et al.</i> (2023)
Awareness program and training	ERes3	0.659				0.650		Kumar <i>et al.</i> (2015), Singh <i>et al.</i> (2021), Mishra (2022), Hariyani & Mishra, (2024), Rathi <i>et al.</i> (2023), and Hussain <i>et al.</i> (2023)
Effective resource allocation	ERes4	0.653				0.679		Pandey <i>et al.</i> (2018), Singh <i>et al.</i> (2021), Yadav <i>et al.</i> (2021), Shokri <i>et al.</i> (2022), Letchumanan <i>et al.</i> (2022), and Hussain <i>et al.</i> (2023)
Sharing financial benefits	ERes5	0.645				0.632		Singh <i>et al.</i> (2021) and Mohan <i>et al.</i> (2022)
Supplier management	ELnk1	0.762					0.676	Kumar <i>et al.</i> (2015), Parmar & Desai (2020), Kaswan & Rathi (2020b), Digalwar <i>et al.</i> (2020), and Singh <i>et al.</i> (2021)
Customer satisfaction and delight	ELnk2	0.786					0.783	Kumar <i>et al.</i> (2015), Kaswan & Rathi (2020b), Farrukh <i>et al.</i> (2020), and Singh <i>et al.</i> (2021)
Customer demand	ELnk3	0.735					0.711	Kumar <i>et al.</i> (2015), Pandey <i>et al.</i> (2018), Parmar & Desai (2020), Singh <i>et al.</i> (2021), and Ershadi <i>et al.</i> (2021)

(Continued.)

Table 2 | Continued

Enablers	Code	Comm ^a	Factors					References
			1	2	3	4	5	
Link of GLSS with customer/supplier	ELnk4	0.787					0.781	Kumar <i>et al.</i> (2015), Pandey <i>et al.</i> (2018), Singh <i>et al.</i> (2021), and Hariyani & Mishra (2024)
Integrating GLSS in core business	ELnk5	0.787					0.752	Kumar <i>et al.</i> (2015), Farrukh <i>et al.</i> (2019, 2021), Kaswan & Rathi (2020b), Hariyani & Mishra (2024), and Hussain <i>et al.</i> (2023)

^aCommunality.

Table 3 | CFA model fit results.

Factor	χ^2	df	χ^2/df	p-value	GFI	NFI	TLI	CFI	RMSEA	SRMR
GLSS_En	541.71	391	1.385	0.001	0.895	0.925	0.975	0.978	0.036	0.033

Note: χ^2 , Chi-square; df, degree of freedom.

The following analysis involved testing the measurement model for GLSS enablers using CFA. In [Table 3](#), the GLSS construct underwent validation via the maximum likelihood method with multiple factors. The results of the CFA showcased an exceptionally parsimonious model fit, where a χ^2/df value below 3.0 signifies a good fit. Additionally, the incremental fit criteria, including goodness fit index (GFI), normed fit index (NFI), Tucker-Lewis index (TLI), and comparative fit index (CFI), close to or above 0.9, indicated a good fit. The absolute model fit, determined by a significant chi-square (χ^2) value ($p < 0.001$), Root Mean Square Error of Approximation (RMSEA) = 0.036, and Standardized Root Mean Square Residual (SRMR) = 0.033, all falling below 0.08, further supported a good fit. The R^2 values for each indicator ranged between 0.68 and 0.82, as visually depicted in [Figure 2](#). These results imply that these five constructs effectively measure GLSS enablers for implementation in the Malaysian WWTP sector.

Furthermore, construct validity was evaluated through assessments of convergent and discriminant validity. Convergent validity ensures consistent measurement outcomes across various variables and methods (O'Leary-Kelly & Vokurka, 1998). It was confirmed by examining composite reliability (CR) and average variance extracted (AVE) values. $CR > 0.6$, $CR > AVE$, and $AVE > 0.5$ criteria were met by all factors in the model (Hundleby & Nunnally, 1968; [Table 4](#)), affirming convergent validity. Discriminant validity was assessed using the Heterotrait-Monotrait (HTMT) approach, which compares inter-construct correlations (heterotrait) to intra-construct correlations (monotrait). HTMT values ranging from 0.674 to 0.815, all below the 0.9 threshold, indicated satisfactory discriminant validity (Henseler *et al.*, 2015). This conclusion was further supported by factor loadings, AVE, and cross-loadings from previous tables ([Table 2](#)), strengthening the evidence for discriminant validity.

[Table 4](#) outlines the results of GLSS enablers in the Malaysian WWTP sector, presenting various means reflecting respondent perceptions of agreement. The overall mean for each factor was computed to gauge the perceived level of importance of GLSS enablers. These mean values range from 4.310 to 3.949, signifying a good level of agreement on the importance of GLSS enablers. The two highest-rated enablers are Strategic (4.310) and Resource (4.289), followed by Culture (4.269) and Environment (4.051). Conversely, Linkage (3.949) is perceived as the GLSS enabler with the least agreement among respondents.

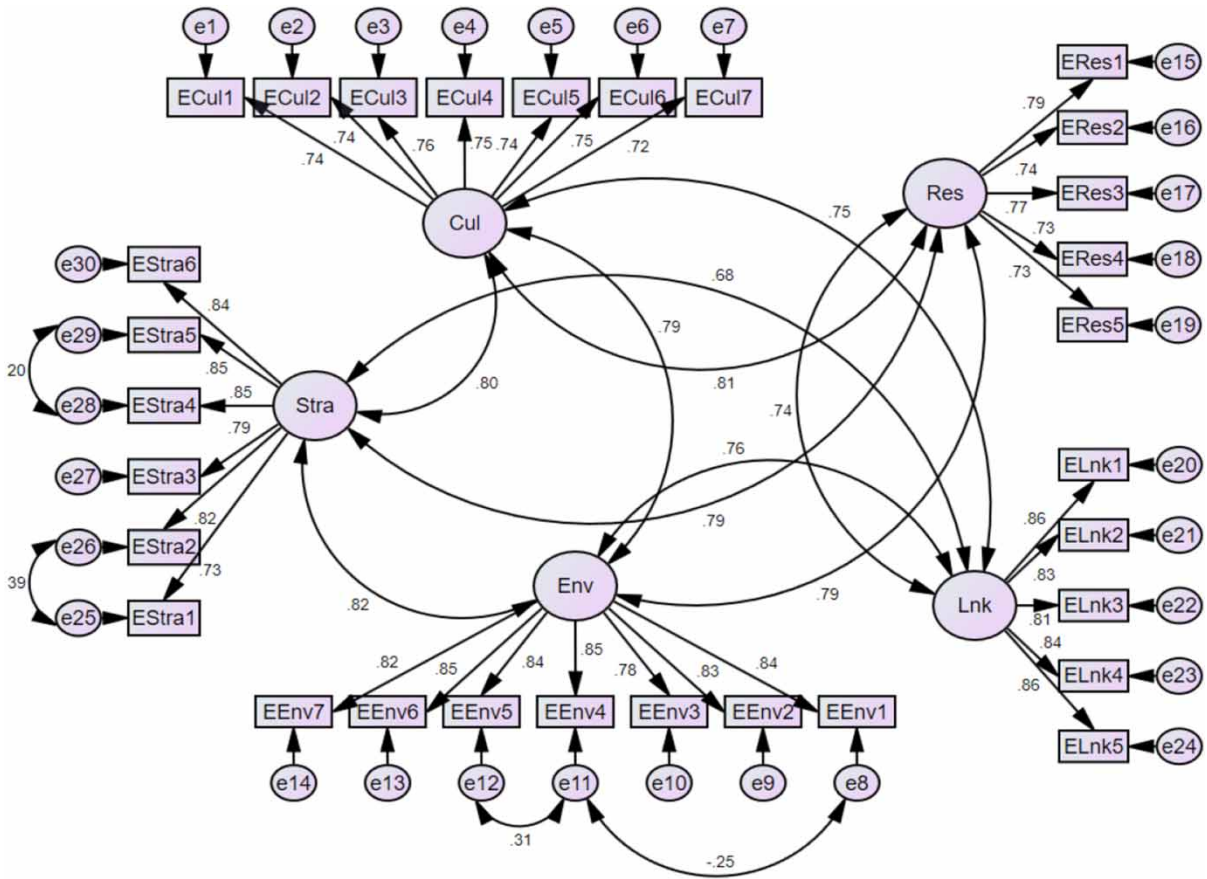


Fig. 2 | CFA diagram for GLSS enabler's model.

Interestingly, the ranking of the top three enablers identified in this study aligns with the analytic hierarchy process (AHP) ranking in Pandey *et al.*'s (2018) research. However, a contrast emerges in this study, as the linkage-based enablers are considered the least significant, with Elnk5, Elnk2, and Elnk4 hitting the lowest mean values. This finding contradicts the outcomes of studies by Kaswan & Rathi (2019), and Rathi *et al.* (2023), where the Interpretive Structural Modeling (ISM)-Matrice d'Impacts Croisés Multiplication Appliquée à un Classement (MICMAC) model and BWM analysis highlighted the integration of GLSS in core business (Elnk5) as among the top enablers in their research.

Respondents emphasize the critical need for a strategic approach to sustainable WWTP operations. Key components include top management commitment (EStra1), effective project leadership (EStra2), and precise data collection (EStra6) within Malaysian contexts. Active support and resource provision by management are important for successful implementation (Kaswan & Rathi, 2019). According to Pandey *et al.* (2018), this strategy enhances profits by streamlining operations. Top management must ensure compliance with current pollution laws, develop plans for future regulations, and integrate technological advancements (Gandhi *et al.*, 2018). Their commitment significantly influences sustainable practices such as utilizing alternative energy and waste reduction (Kaswan & Rathi, 2020a). Consistent effective leadership is crucial in implementing manufacturing

Table 4 | Average GLSS enabler's importance rating and CFA results.

Factors	Mean	SD	Average mean	Average SD	Rank	Standard estimates	CR	AVE
<i>Strategic (Stra)</i>			4.310	0.651	1		0.921	0.660
EStra1	4.476	0.627				0.727		
EStra2	4.348	0.687				0.819		
EStra3	4.233	0.696				0.786		
EStra4	4.236	0.631				0.849		
EStra5	4.230	0.623				0.850		
EStra6	4.334	0.643				0.836		
<i>Environment (Env)</i>			4.051	0.705	4		0.940	0.689
EEnv1	4.101	0.720				0.840		
EEnv2	3.973	0.722				0.828		
EEnv3	4.101	0.739				0.783		
EEnv4	4.044	0.700				0.848		
EEnv5	3.946	0.720				0.844		
EEnv6	4.105	0.658				0.846		
EEnv7	4.088	0.673				0.821		
<i>Culture (Cul)</i>			4.269	0.577	3		0.896	0.552
ECul1	4.301	0.553				0.742		
ECul2	4.682	0.508				0.735		
ECul3	4.402	0.591				0.757		
ECul4	4.135	0.612				0.753		
ECul5	4.068	0.554				0.743		
ECul6	4.037	0.590				0.752		
ECul7	4.257	0.628				0.716		
<i>Resource (Res)</i>			4.289	0.582	2		0.868	0.568
ERes1	4.264	0.662				0.793		
ERes2	4.128	0.568				0.739		
ERes3	4.372	0.556				0.770		
ERes4	4.527	0.552				0.730		
ERes5	4.152	0.571				0.735		
<i>Linkage (Lnk)</i>			3.949	0.732	5		0.924	0.708
ELnk1	4.074	0.695				0.857		
ELnk2	3.841	0.749				0.834		
ELnk3	4.172	0.709				0.814		
ELnk4	3.760	0.764				0.840		
ELnk5	3.895	0.745				0.863		

philosophies across the organization. Accurate data collection and assessment of Lean and Green waste are crucial for thorough system analysis (Kaswan & Rathi, 2020a), assessing eco-efficiency using specific tools (Farrukh *et al.*, 2021).

The key facilitators for successful GLSS implementation revolve around essential resources, playing the second most crucial role in the sustainable process. This includes securing resource allocation (ERes4) like funding (Kumar *et al.*, 2015; Hussain *et al.*, 2023), providing necessary awareness training (ERes3) for employee skills (Singh *et al.*, 2021), and external support, such as consultant expertise (Pandey *et al.*, 2018). Thoughtful financial planning by management ensures adequate allocation of resources to meet project goals (Yadav *et al.*, 2021). This planning involves initial investments in technology, estimating tools, and staff training, emphasizing the efficient use of finances for comprehensive GLSS adoption (Letchumanan *et al.*, 2022; Shokri *et al.*, 2022). Mastery through understanding and practical application of GLSS methodology (ERes1) is also important for successful adoption (Hussain *et al.*, 2023).

In the context of Malaysian WWTPs, culture-based elements rank third, while environmental factors follow as the fourth most critical enablers. Respondents stress teamwork (ECul2) (Kaswan & Rathi, 2019), effective communication (ECul3) (Pandey *et al.*, 2018), and strategic team selection (ECul1) in GLSS as important (Letchumanan *et al.*, 2022; Mishra, 2022). Embracing diverse employee skills is key to enhancing organizational culture (Singh *et al.*, 2021). Strong teamwork cultivates adaptability, confidence in new approaches, and solid employee relations amidst business changes emphasized by Singh *et al.* (2021). Employee involvement ensures cooperative cultures, key to successful GLSS adoption (Rathi *et al.*, 2023). Transparent communication, facilitated by an efficient organizational structure, supports positive work environments (Hariyani *et al.*, 2023). In addition, companies respond to eco-friendly demands by adopting strategies like efficient manufacturing, green procurement, and waste reduction (Pandey *et al.*, 2018). This approach mitigates costs amid market unpredictability (Kumar *et al.*, 2015; Hariyani & Mishra, 2023).

The lowest agreement was observed regarding linkage-based enablers, as seen in Habidin & Yusof (2013), specifically in supplier relationships. Connecting GLSS with customers and suppliers (ELnk4) and prioritizing customer satisfaction (ELnk2) scored lowest in this study. A notable decrease in consumer complaints reflects a customer-focused social performance (Pandey *et al.*, 2018), emphasizing product responsibility (Farrukh *et al.*, 2020). Organizations supporting suppliers' environmental shifts through training, workshops, and financial aid (Hussain *et al.*, 2023) foster long-term customer relationships by responding to their expectations and concerns (Farrukh *et al.*, 2021).

5. CONCLUSION

This study aims to assess the enablers influencing GLSS implementation in Malaysia's wastewater treatment industry, which are crucial for ensuring effective implementation and reaping associated benefits. Understanding the complex and diverse elements affecting GLSS implementation is essential. Data from 296 certified professionals in Malaysian WWTPs were utilized, and SEM validated the research model through EFA, CFA, reliability, and model fit tests, confirming the factors' validity and reliability. The study reveals five significant enablers for GLSS implementation in Malaysian WWTPs. Overall, the majority of Malaysian WWTPs demonstrated a moderate to high level of agreement in GLSS adoption, signalling positive progress in enhancing sustainable performance.

Theoretical implications of this research enrich specialized literature through the originality of the CFA model, allowing examination of GLSS enabler dimensions in the context of WWTP operation. Particularly, the 'strategic' and 'resource' enablers emerged as highly crucial for GLSS implementation in Malaysian WWTPs. Key components include top management commitment, effective project leadership, and precise data collection within

Malaysian contexts. Active support and resource provision by management are important for successful implementation (Kaswan & Rathi, 2019). Moreover, securing resource allocation and funding (Kumar *et al.*, 2015; Hussain *et al.*, 2023), providing necessary awareness training for employee skills (Singh *et al.*, 2021), and external support, such as consultant expertise, are essential (Pandey *et al.*, 2018). Thoughtful financial planning by management ensures adequate allocation of resources to meet project goals (Yadav *et al.*, 2021). The research findings are robust and support the stability of the proposed conceptual CFA model.

Besides theoretical implications, this study also reveals practical implications. It provides a clear picture for WWTP organizations to adopt GLSS enablers for sustainable operations, prioritizing GLSS strategies to improve wastewater treatment processes. WWTP top management should support their teams in fostering effective teamwork, communication, and scheduling through initiatives like employee retention, empowerment, and knowledge sharing, creating a more conducive environment for sustainability-focused organizational culture and ethics. Integrating GLSS into core business strategies aligns with environmental, social, and corporate governance principles to support Sustainable Development Goals.

This study has limitations worth noting and suggests future research directions. First, the sample comprises WWTP professionals only from Malaysia, limiting generalizations attributable to specific country characteristics, culture, and the degree of GLSS implementation. Future research should conduct cross-country comparative analyses to ascertain the universality of the proposed model. Second, exploring the structural relationship between these enablers and sustainable performance in future research is planned. Developing sustainable performance metrics considering economic, environmental, and social aspects will aid the WWTP industry in evaluating its sustainable performance. Future research aims to address these limitations by combining the use of quantitative methods.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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