

ISSN 1840-4855

e-ISSN 2233-0046

Original scientific article

<http://dx.doi.org/10.70102/afts.2026.1836.363>

INTEGRATING LEAN THINKING AND GREEN MANUFACTURING FOR SUSTAINABLE ENVIRONMENTAL PERFORMANCE IMPROVEMENT

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Received: May 13, 2026; Revised: June 22, 2026; Accepted: August 03, 2026; Published: September 29, 2026

SUMMARY

The issue of environmental sustainability is now a challenge for manufacturers in developing economies, in which the use of resources is high and the use of cleaner technologies is not widespread. Little evidence of how lean thinking translates into environmental outcomes in the context of green manufacturing is found, especially in the Iraqi industrial sector. This study aims to investigate the impact of Lean Thinking (LT) on Environmental Sustainability (ES) and mediate the environmental impact of Green Manufacturing (GM) in Apparel Factories in Najaf, Iraq. A quantitative cross sectional survey was conducted using a five point likert scale questionnaire with 45 items randomly sent to 250 employees of which 145 questionnaires were returned (response rate-90.6%). Higher-order constructs were employed in the analysis of data using partial least squares structural equation modelling (PLS-SEM) software program "SmartPLS 4". The range of the composite reliability was 0.801 to 0.970 while all the heterotrait–monotrait ratios were less than 0.90. LT had a significant positive effect on ES ($\beta = 0.376$, $t = 5.415$, $p < 0.001$) and on GM ($\beta = 0.797$, $t = 15.331$, $p < 0.001$), and GM significantly affected ES ($\beta = 0.603$, $t = 8.624$, $p < 0.001$). The indirect effect of LT on ES through GM was significant ($\beta = 0.481$, $p < 0.001$) and accounted for 56.1% of the total effect, meaning that GM partially mediated LT's effect on ES. The model explained 63.5% of the variance in GM and 86.7% in ES ($Q^2 = 0.365$; SRMR = 0.077). The results indicate that the best environmental impacts of lean thinking can be achieved through green manufacturing capabilities, providing an integrated lean–green strategy for apparel manufacturers in the developing economies.

Key words: *lean thinking, green manufacturing, environmental sustainability, mediation analysis, pls-sem, apparel industry, iraq.*

INTRODUCTION

Industrial activities have led to environmental degradation, which has emerged as one of the biggest challenges of the decade. Manufacturing is a high material and energy consumer, source of solid waste, effluents and emissions, and accounts for a significant proportion of the burden, especially in developing economies, where environmental regulation, infrastructure and technological capacity are still developing [1] [2]. The textile and apparel industry is particularly vulnerable due to the high consumption of resources and overproduction, textile fabric waste and processing energy consumption [3]. In Iraq, the apparel factories of Najaf Governorate is one of the most significant apparel production clusters in the nation and is trying to move towards sustainability despite facing a lot of economic and infrastructure challenges. Green finance adoption plays a critical role in driving sustainable economic development and modern corporate strategy [27].

Lean thinking is a concept that originated in the Toyota Production System, with the goal of achieving the maximum value to the customer by systematically eliminating activities that do not add value to the system [2]. Like overproduction, overstocking, defect, and unnecessary transport, the consumption of materials and energy are taken up by all Lean waste, which is why Lean is referred to as a natural catalyst for green operations [4]. The application of environmental criteria in technology selection, energy consumption, system configuration and product life cycle management, as shown in green manufacturing, is further embedded. Both paradigms share the common vision of optimal utilization of resources, without causing harm to the environment.

Although there is a conceptual continuum, there are three problems that are restricting the understanding. First, studies of lean-green have been largely limited to the industrial sectors of developed or large emerging economies, and there are only a few studies looking at labour-intensive sectors such as the apparel industry in the Middle East [1][6]. Second, there are inconclusive empirical findings: some studies have observed a direct effect of lean on environmental performance, while others have found that the impact is mainly through environmental or green practices [7] [8] [9]. Third, lean has been traditionally defined as a collection of tools at the shop floor, while lean thinking as a socio-technical philosophy in terms of behaviours, procedures and skills has been much less studied [10]. This means the pathway from lean thinking to environmental sustainability is yet to be precisely defined. Thus the research problem can be formulated as: How much lean thinking help in increasing the environmental sustainability in the Iraqi apparel factories and does green manufacturing spread the effect?

Based on this, the study aims at three things: (i) to measure the level of lean thinking, green manufacturing and environmental sustainability in the apparel factories of Najaf; (ii) to estimate the direct effects of lean thinking on green manufacturing and on environmental sustainability, and of green manufacturing on environmental sustainability; and (iii) to test and quantify the mediating role of green manufacturing between lean thinking and environmental sustainability.

This study makes three contributions. On the theoretical level, it suggests and validates an integrated higher-order model that positions lean thinking (Lean behaviours, procedures and skills) as an enabling capability which is transformed to environmental outcomes through the four green manufacturing capabilities, thus specifying a mechanism, which is not described in the previous lean-green models. Practically, it offers the first empirical evidence in support of this mechanism in the context of the apparel industry in Iraq using PLS-SEM, and it breaks down the total effect of lean thinking into its direct and indirect effects. In practice, it could be used to pinpoint the "lean and green" levers that managers and policy makers should focus on to better enhance resource efficiency and pollution prevention.

The remainder of the paper is organised as follows. Section 2 reviews the literature, identifies the research gap and develops the hypotheses. The methodology covered in section 3, which included sampling procedure, design of the questionnaire, measurement scales and the data collection, explained the methodology used. The results of the measurement model, structural model and mediation analysis are presented in section 4. Section 5 discusses the findings, compares them with previous studies and

outlines the theoretical and practical implications and the limitations. The paper is concluded in Section 6, with directions for future research.

LITERATURE REVIEW AND HYPOTHESES DEVELOPMENT

Lean Thinking

The aim of lean thinking is to remove waste and continually improve to maximise customer value – it is a holistic socio-technical approach [2]. It is usually summarized in five principles: Defining value from customer's point of view, mapping the value stream, creating flow, establishing pull, and pursuing perfection. Early studies focused on “hard” tools like value stream mapping (VSM), 5S, single-minute exchange of die (SMED), kanban and total productive maintenance (TPM) and found that some of these tools also contribute to reducing material, energy and waste intensity [11] [12] [22]. More recent research states that the “soft”, human-centred part of lean – such as leadership behaviours, employee involvement and problem solving – is critical for maintaining the improvements and for addressing barriers in achieving environmental performance [10].

Lean thinking is here conceptualized in terms of three dimensions in accordance with this socio-technical perspective. Lean behaviours are the processes for continuous improvement (kaizen) and respect for people that eliminate ambiguity and make roles in operations clear. Lean procedures are the standardisation of the use of lean tools, including VSM, and the systematic elimination of the seven wastes, to make process waste visible and measurable [13]. Lean skills are employee's abilities in solving problems and simple statistical analysis that allows them to identify and eliminate the key causes of waste. Most of the literature so far addresses either the tools or the attitude of lean, and few studies report on the behavioural and technical aspects of lean at the same time, so the real-world application of lean has not been explained as to why the same tools lead to various environmental outcomes in different firms [2] [10].

Green Manufacturing

Green manufacturing is a manufacturing paradigm in which the organisation designs and runs its manufacturing processes to avoid harmful impact on the air, soil and water, to save natural resources and to make manufacturing processes economical [5] [14]. The idea is not confined to product alone, but to the whole manufacturing system and to the product life cycle. In this regard, green manufacturing is defined as four capabilities as mentioned by Belhadi et al. [5]. Green tools and technologies are monitoring sensors, cleaner process technologies and non-toxic materials that detect and manage environmental impacts. Energy saving technologies include energy efficient machinery and energy recovery systems. Reconfigurable manufacturing systems enable production lines to be easily reconfigured to meet new environmental requirements and product mixes with minimal scrap and set-up losses. Life-cycle management (LCM) is concerned with environmental issues that occur throughout the design, production, and end-of-life of a product, including recycling and reuse.

Empirical studies report that green manufacturing practices enhance the sustainable performance, in part, through their ability to stimulate green innovation [14] and that lean and green practices work hand-in-hand to drive process innovation and green supply chain performance [15]. However, the green manufacturing literature is largely focused on these investments in technology based on regulation and there has been little focus on the organisational routines and skills that influence whether or not these investments are accepted on the shop floor. This is exactly where Lean comes in; Lean is the process discipline and improvement culture on which green practices can be built [4] [24].

Environmental Sustainability

Environmental sustainability is defined as the responsible use of natural resources to satisfy the needs of current generations while preserving the capacity of future generations to satisfy their needs, and this is a balance that must be struck between environmental integrity, social well-being and economic viability. It is expressed at the organisational level as the amount of water, energy and materials saved

and the reduction of pollutants and waste prevented by a firm. The findings of the meta-analysis indicate that there is a positive relationship between environmentally sustainable practices and firm performance, thereby reinforcing the business case for environmentally sustainable practices [16]. This study adopts two dimensions in operationalising the term environmental sustainability. Resource efficiency reflects optimisation of material and energy use and incorporates principles of circular economy in the sense that it includes re-use and re-cycle, while pollution prevention reflects the reduction of emissions, effluents and hazardous substances "upstream" (at the source) instead of "downstream" (at the end of the pipe). In the context of apparel production, off-cuts from fabric, overproduction, and energy use during finishing are the key impacts on the environment, for both dimensions [3].

Critical Synthesis and Research Gap

The lean–green–sustainability nexus has been explored in three avenues of empirical research. The first stream examines the direct environmental impact of lean practices and tends to show positive correlations though there are some differences in magnitude for different tools and sectors [11] [12] [26]. The second stream adds intervening variables such as environmental/green practices. Our findings agree with those of Yang et al. [7] who reported that lean experience was positively correlated with environmental management practices, which in turn were positively correlated with environmental performance, and that of Hajmohammad et al. [8] who reported that lean management had indirect influence on environmental practices that further influenced environmental performance, and that of Inman and Green [9] who found the indirect effect of lean experience on environmental performance via green practices was greater than the direct effect. The third stream involves conceptual models and systematic review articles that call for the integration of lean and green in non-researched areas and regions, but require empirical validation [1] [6] [23]. The present work is motivated by the four limitations that are observed from these studies. First, lean is not primarily about a way of thinking that integrates behaviours, procedures and skills, but is largely measured by hard tools. Second, the mediator is not generally defined at the internal green manufacturing capabilities level, but at supply-chain level (green supply chain management) or as generic environmental management. Third, the evidence is largely from auto, electronics and diversified manufacturing samples in North America, Europe and Asia, and virtually non-existent across labour intensive apparel factory developing countries across Middle East. Fourth, most studies only investigate significance rather than break down total effect into direct and indirect effects, or gross effect size and predictive relevance.

The research gap addressed in this study is that no higher order model has been validated using data to explain how lean thinking is translated into environmental sustainability within internal green manufacturing capabilities in apparel manufacturing in a developing economy like Iraq. This novelty of the study is carried out in the following points: (i) modelling lean thinking, green manufacturing and environmental sustainability as higher-order constructs with nine first-order dimensions, with the reflective–reflective framework; (ii) explicitly theorizing and quantifying the mediating mechanism, as well as its direct, indirect and total effects; and (iii) providing the first such evidence in the context of Iraqi apparel factories.

Theoretical Foundation and Hypotheses

Lean Thinking and Environmental Sustainability

Lean thinking and environmental sustainability share the same underlying logic, since both treat the Waste of resources, that is, unneeded use of resources. Corresponding to each lean waste, there exists an environmental waste: overproduction or excess inventory wastes raw materials or energy, which may never produce value; defects and rework waste material and energy; unnecessary transport and motion wastes fuel and electricity [2] [4]. Only "Lean procedures" like VSM "makes these flows visible", "Lean behaviours" helps to sustain continuous improvement, and "Lean skills" allows employees to remove root causes. Lean practices like VSM, SMED, TPM and cellular manufacturing have been shown in empirical studies to decrease the intensity of material, energy and waste; a production-cell level integrated lean and green intervention has been shown to reduce resource use by 30-50% on average [11] [12] [13]. Hence, the following hypothesis is proposed.

H1: Lean Thinking positively and significantly affects Environmental Sustainability.

Lean Thinking and Green Manufacturing

There are three reasons why lean thinking is expected to promote green manufacturing. Lean procedures have resulted in stable and standardised processes which are a prerequisite to measuring and improving mass and energy flows [13]. Secondly, the culture of continuous improvement and problem solving common among lean employees enables the organisation to be able to identify, acquire and adapt green tools, energy saving technologies and reconfigurable systems [10]. Third, green practices and environmental management have been shown to have a positive correlation with lean practices [7] [8]. Lean thinking can thus serve as a catalyst for greening operations [4] and the following hypothesis arises.

H2: Lean Thinking positively and significantly affects Green Manufacturing.

Green Manufacturing and Environmental Sustainability

Green manufacturing capabilities directly influence both dimensions of the environmental sustainability. Energy-saving technologies and Green tools lower emissions and energy intensity, reconfigurable systems minimize scrap and set-up losses, and life-cycle management encourages reusing, recycling, and replacing hazardous materials: all contribute to better resource efficiency and pollution prevention [5]. The empirical studies have found and reported that Green manufacturing and Green supply chain practices are beneficial to enhancing environmental and sustainable performance [9][14][18]. Both are interconnected but distinct, green manufacturing is about specific practices, technologies and processes, while environmental sustainability is about the overall outcome to which these practices contribute. Hence, the following hypothesis is proposed.

H3: Green Manufacturing positively and significantly affects Environmental Sustainability.

The Mediating Role of Green Manufacturing

The role of green manufacturing as a mediator has its foundations in the logic of capability building from the resource-based view [14] and the argument of complementarity of lean–green research [4] [9]. Lean thinking is a mental state that is considered to be the basis of lean and is not entirely tangible, it is a mix of behaviours, procedures and skills that have the power to enhance the stability, transparency and improvement capacity of the process, but it does not comprise environmental technologies. Environmental sustainability, on the other hand, is a desired result that depends on certain environmental proficiencies, including efficient use of energy and equipment, cleaner technologies, flexible manufacturing and life cycle processes. The method of transitioning from the former to the latter is called “green manufacturing”.

There are three steps in the causal chain. First, VSM, Lean procedures, waste walks, etc. identify material, energy and emissions loss. Second, lean behaviours and skills provide the problem solving ability and employee commitment to select, install and continually develop green technologies and reconfigurable systems. Third, these “green” manufacturing capabilities help to lower the consumption of resources and pollution at the source. It is also expected that the influence of lean thinking will remain direct on improving environmental sustainability, as the elimination of waste alone (for instance, fewer defects, less overproduction, etc.) brings environmental benefits without the need to invest in new green technologies. This means that only a partial mediation is expected, similar to previous lean–green investigations [9]. This suggests the following hypothesis.

H4: Green Manufacturing positively and significantly mediates the relationship between Lean Thinking and Environmental Sustainability.

The model for the proposed research is shown in figure 1. The exogenous Higher Order construct is lean thinking; the mediating construct is green manufacturing while the endogenous outcome is environmental sustainability. The direct routes between lean thinking and environmental sustainability

are H1, H2 and H3, with H4 being the indirect route from lean thinking to environmental sustainability via green manufacturing.

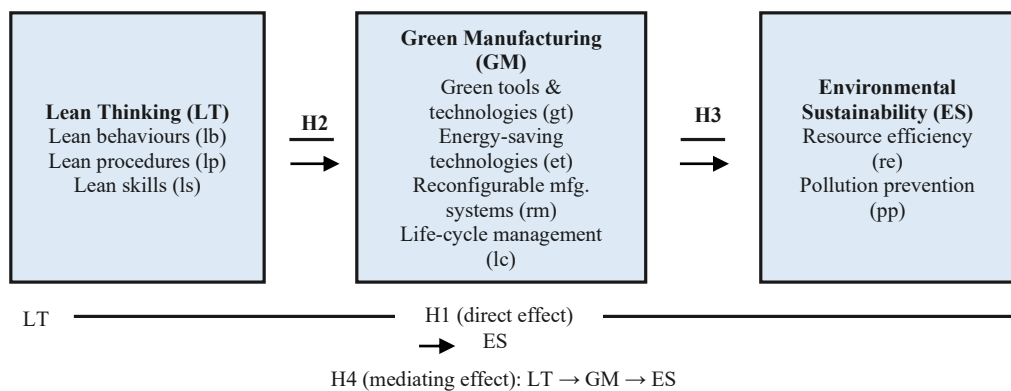


Figure 1. Proposed research model and hypotheses

RESEARCH METHODOLOGY

Research Design

A quantitative, explanatory and cross-sectional survey design was used because the aim of the study was to test the hypotheses derived from the theory about the relations among the latent constructs. The unit of analysis was the individual employee, and their perceptions of lean, green and environmental practices at the factory level was measured by a structured questionnaire.

Population, Sampling Procedure and Sample Size

The research was carried out in the apparel factories in the Governorate of Najaf in Iraq under the responsibility of the Ministry of industry and minerals in Iraq. According to the records of the Industrial Research and Development Authority (Industrial Statistics Report, 2023), the target population were all 250 employees in three workshops, the Developed Suit Workshop, the Military Products Workshop and the Medical Products Workshop. A combined list of all employees across the three workshops was generated from employee registers and simple random sampling was used to select employees in this sample, ensuring they all had an equal chance of being picked. One hundred and forty-five (145) questionnaires were received (90.6% response rate).

The enoughness of the sample size was checked using the inverse square root method recommended for PLS-SEM. At the smallest path coefficient in the model ($\beta = 0.376$), the minimum sample size (N) needed, assuming a 5% significance level and 80% statistical power is $(2.486/0.376)^2 = 145$ respondents and the actual number obtained is more than three times that number. The ten times rule is also met with the sample, as the maximum number of structural paths for any construct is two (minimum $n = 20$).

Questionnaire Design and Measurement Scales

This questionnaire was divided into two parts. Data in Section A is related to the demographic and occupational attributes of the respondents (age, gender, job position, job experience). Section B consisted of 45 items (from established scales and contextualised to apparel manufacturing) that measured the three constructs (Table 1). Responses to all items were provided on a five-point Likert scale with the scores 1 (strongly disagree) to 5 (strongly agree). The 15 items of lean thinking were taken from operationalisations of lean thinking as a socio-technical system and adapted for apparel context and were classified to lean behaviours, lean procedures and lean skills. In this study, 20 items, based on the dimensions suggested by Belhadi et al. [5], were used to measure the green manufacturing. The environmental sustainability aspect was assessed using 10 items, covering aspects of resource efficiency and pollution prevention, and was adapted from the environmental performance measures from

empirical lean–green resear. All items were rewritten to use the terminology of garment production to ensure that they were understood in the same way across all organizational levels.

Table 1. Structure of the measurement instrument

Construct	Dimension (code)	Items	Item codes	Source
Lean Thinking (LT)	Lean behaviours (lb)	5	LT-lb1 – LT-lb5	[2]
	Lean procedures (lp)	5	LT-lp1 – LT-lp5	[10]
	Lean skills (ls)	5	LT-ls1 – LT-ls5	
Green Manufacturing (GM)	Green tools and technologies (gt)	5	GM-gt1 – GM-gt5	[5]
	Energy-saving technologies (et)	5	GM-et1 – GM-et5	
	Reconfigurable manufacturing systems (rm)	5	GM-rm1 – GM-rm5	
	Life-cycle management (lc)	5	GM-lc1 – GM-lc5	
Environmental Sustainability (ES)	Resource efficiency (re)	5	ES-re1 – ES-re5	[7] [9]
	Pollution prevention (pp)	5	ES-pp1 – ES-pp5	
Total: 3 constructs, 9 dimensions, 45 items; five-point Likert scale (1 = strongly disagree, 5 = strongly agree)				

Table 1 demonstrates the inclusion of five reflective items for each of the nine first-order dimensions, providing a balanced instrument and also that the number of indicators exceeds the minimum three per construct required to reliably estimate the construct. The number of items per construct (15, 20 and 10) corresponds to the number of dimensions in each conceptual framework.

Data Collection Procedure

The questionnaires were issued to the employees of the three workshops, who were selected at random and were collected after they had filled them out, with the permission of the factory management. Data prior to analysis were screened for missing items and outliers, and those that were problematic were eliminated, leaving 145 cases to be analyzed.

Data Analysis Technique

PLS-SEM was chosen due to the study's explanatory and prediction nature, the presence of higher-order constructs and the fact that the method is non-distributional and it works well with moderate sample sizes. The data analysis employed in this study is SmartPLS 4. The three constructs were defined as reflective–reflective higher-order constructs with the repeated indicators approach. Two-step procedure was used. The measurement model was evaluated based on indicator loadings, internal consistency reliability (composite reliability, CR), convergent validity (average variance extracted, AVE) and discriminant validity (heterotrait–monotrait ratio, HTMT) [20]. In this study, the reliability of constructs was measured by composite reliability rather than Cronbach's α , because the latter is prone to underestimate reliability in the presence of unequal indicator loadings, which is a feature of PLS-SEM. The structural model was then validated using collinearity tests (VIF), size and significance of path coefficients with a bootstrapping of 5,000 subsamples of the data, coefficient of determination (R^2), effect size (f^2), predictive relevance (Q^2) and model fit (SRMR). Mediation was evaluated based on the work of Nitzl et al. [24] and by testing the significance of the indirect effect using bootstrapping, and the type of mediation as a function of the significance and sign of the direct effect, the variance accounted for (VAF) was reported as an additional indicator of the magnitude of mediation.

RESULTS

Respondent Profile

The respondents were 145 in total and their profile is summarized in table 2. Sixty-nine percent of the sample was male and 31% was female. The largest age groups were under 25 years (30.3%) and 35–44 years (26.2%), while only 4.8% were 55 years or older. More than one third of the respondents were in

a position of authority, either as supervisors (26.9%) or managers (11.7%), and had an understanding of production decisions, compared to 61.4% who were regular employees. Speaking of experience, 40.7% had 1-3 years and 30.3% had 4-6 years while 15.9% had more than six years of experience. The sample is therefore representative across all levels of the organisation and across all experience categories and this helps the representativeness of the perceptions that were collected.

Table 2. Demographic profile of respondents (n = 145)

Characteristic	Category	Frequency	Percentage (%)
Age	Under 25	44	30.3
	25–34	28	19.3
	35–44	38	26.2
	45–54	28	19.3
	55 and above	7	4.8
Gender	Male	100	69.0
	Female	45	31.0
Job position	Regular employee	89	61.4
	Supervisor	39	26.9
	Manager	17	11.7
Experience	Less than 1 year	19	13.1
	1–3 years	59	40.7
	4–6 years	44	30.3
	More than 6 years	23	15.9

Descriptive Statistics

The mean, SD (mean/5) and RII (mean/5) of constructs and dimensions are reported in table 3 along with the item level mean and SD. All three constructs were rated at a high level: environmental sustainability (M = 3.945, SD = 0.529, RII = 0.789), green manufacturing (M = 3.940, SD = 0.608, RII = 0.788) and lean thinking (M = 3.844, SD = 0.529, RII = 0.769). Pollution prevention (RII: 0.795) and green tools and technologies (RII: 0.790) and energy-saving technologies (RII: 0.784) had higher RII values than lean behaviours (RII: 0.767) at dimension level.

Table 3. Descriptive statistics of constructs, dimensions and items

Construct / dimension	Mean	SD	RII	Item 1 M (SD)	Item 2 M (SD)	Item 3 M (SD)	Item 4 M (SD)	Item 5 M (SD)
Environmental Sustainability (ES)	3.945	0.529	0.789					
Resource efficiency (re)	3.914	0.553	0.783	3.841 (0.574)	3.779 (0.513)	3.938 (0.525)	4.048 (0.600)	3.972 (0.559)
Pollution prevention (pp)	3.975	0.501	0.795	3.979 (0.520)	3.959 (0.474)	3.972 (0.506)	4.007 (0.462)	3.959 (0.543)
Green Manufacturing (GM)	3.940	0.608	0.788					
Green tools & technologies (gt)	3.949	0.566	0.790	4.028 (0.629)	3.903 (0.604)	4.021 (0.433)	3.841 (0.647)	3.952 (0.517)
Energy-saving technologies (et)	3.921	0.528	0.784	3.966 (0.627)	3.952 (0.548)	3.862 (0.394)	3.924 (0.496)	3.903 (0.577)
Reconfigurable mfg. systems (rm)	3.897	0.423	0.779	3.814 (0.481)	3.897 (0.494)	3.876 (0.450)	3.828 (0.423)	3.891 (0.553)
Life-cycle management (lc)	3.869	0.542	0.774	3.766 (0.522)	4.110 (0.956)	4.221 (0.968)	4.179 (0.939)	3.862 (0.443)
Lean Thinking (LT)	3.844	0.529	0.769					
Lean behaviours (lb)	3.834	0.533	0.767	3.903 (0.502)	3.766 (0.614)	3.848 (0.504)	3.869 (0.491)	3.907 (0.545)
Lean procedures (lp)	3.910	0.549	0.782	3.945 (0.498)	3.855 (0.600)	3.828 (0.571)	4.000 (0.506)	3.920 (0.579)
Lean skills (ls)	3.897	0.535	0.779	3.883 (0.599)	4.007 (0.633)	3.862 (0.529)	3.952 (0.599)	3.945 (0.529)

Note: M = mean; SD = standard deviation; RII = relative importance index (mean/5). Item k refers to the item code with suffix k (e.g., Item 1 of re = ES-re1). The RII of each item equals its mean divided by 5.

The range of item was from 3.766 to 4.221 and all SDs were less than 1.0, which implied generally positive and relatively homogeneous perceptions. The relatively low rating of lean behaviours (RII = 0.782) compared to lean procedures (RII = 0.829) indicates that the cultural aspect of lean is not as developed as the procedural aspect in the factories studied.

Measurement Model: Reliability and Convergent Validity

The first order measurement model is presented in table 4. There were 42 indicators with loadings > the recommended 0.708 (between 0.814 and 0.923) and all loadings were significant ($p < 0.001$) of the 45 indicators. All dimensions of composite reliability were above the threshold of 0.70, including life-cycle management (0.801), reconfigurable manufacturing systems (0.956) [19]. Convergent validity was supported in eight of the nine dimensions, with an AVE greater than 0.50 (AVE's ranged from 0.710–0.812). The exception is life cycle management (AVE = 0.463, indicator loadings GM-lc3 = 0.500, GM-lc4 = 0.471, GM-lc5 = 0.577) since its convergent validity is marginal. However, these were retained based on acceptable composite reliability (CR = 0.801) and the conceptual significance of these items as constructs in life cycle management, although this is stated as one of the structural weaknesses in Section 5.5.

Table 4. First-order measurement model: indicator loadings, reliability and convergent validity

Dimension	Item 1	Item 2	Item 3	Item 4	Item 5	CR	AVE
Lean behaviours (lb)	0.890	0.892	0.875	0.902	0.871	0.948	0.785
Lean procedures (lp)	0.853	0.892	0.864	0.866	0.874	0.940	0.757
Lean skills (ls)	0.843	0.824	0.841	0.848	0.857	0.925	0.710
Green tools & technologies (gt)	0.863	0.850	0.901	0.877	0.856	0.939	0.756
Energy-saving technologies (et)	0.814	0.837	0.919	0.868	0.851	0.933	0.737
Reconfigurable mfg. systems (rm)	0.906	0.877	0.923	0.893	0.906	0.956	0.812
Life-cycle management (lc)	0.878	0.859	0.500	0.471	0.577	0.801	0.463
Resource efficiency (re)	0.819	0.859	0.851	0.829	0.856	0.925	0.710
Pollution prevention (pp)	0.854	0.880	0.863	0.887	0.871	0.940	0.759

Note: Item k refers to the indicator with suffix k (e.g., Item 1 of lb = LT-lb1). All loadings are significant at $p < 0.001$ (bootstrapping). CR = composite reliability (pc); AVE = average variance extracted. Thresholds: loading ≥ 0.708 , CR ≥ 0.70 , AVE ≥ 0.50 [19].

These higher-order latent constructs were found to have composite reliability values of 0.970 for LT, 0.964 for GM, and 0.950 for ES, with respective AVEs being 0.686, 0.585, and 0.657. Although the above values indicate excellent consistency of measures, any composite reliability greater than 0.95 may be an indication of possible redundant items and collinearity among the indicators. This indicates that there might be overlapping semantic content in some first-order dimensions/indicators, which will be discussed in the limitations section.

Figure 2 shows the significance of various dimensions related to lean thinking, green manufacturing, and environmental sustainability in terms of their respective RII scores. It can be seen that the dimensions of pollution prevention, green technology, and resource efficiency contribute significantly towards environmental sustainability, whereas lean behaviors are relatively less significant compared to the other assessed dimensions (Table 5).

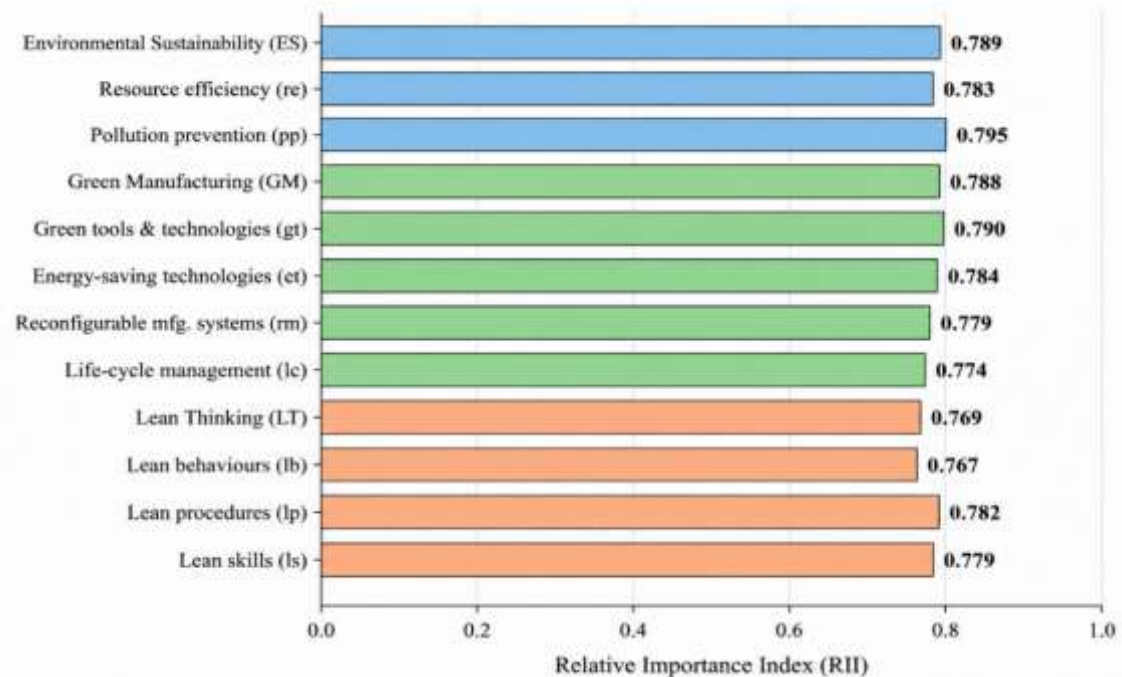


Figure 2. Relative importance index analysis of lean thinking, green manufacturing, and environmental sustainability dimensions

Table 5. Higher-order measurement model

Higher-order construct	First-order dimension	Second-order loading	R ² of dimension	CR	AVE
Lean Thinking (LT)	Lean behaviours (lb)	0.952	0.907	0.970	0.686
	Lean procedures (lp)	0.963	0.928		
	Lean skills (ls)	0.954	0.909		
Green Manufacturing (GM)	Green tools & technologies (gt)	0.894	0.798	0.964	0.585
	Energy-saving technologies (et)	0.953	0.908		
	Reconfigurable mfg. systems (rm)	0.946	0.894		
	Life-cycle management (lc)	0.880	0.774		
Environmental Sustainability (ES)	Resource efficiency (re)	0.943	0.888	0.950	0.657
	Pollution prevention (pp)	0.949	0.900		

Note: Second-order loadings and R² values are taken from the SmartPLS output; all second-order loadings are significant at $p < 0.001$. The R² of a dimension equals the square of its second-order loading.

Discriminant Validity

To evaluate the discriminant validity, the HTMT criterion was used, which is better at variance-based SEM than the Fornell-Larcker criterion. As shown in table 6, the HTMT values between the three higher-order constructs were 0.827 (LT–GM), 0.866 (GM–ES) and 0.898 (LT–ES), all below the threshold of 0.90 recommended for conceptually similar constructs. The highest value between a dimension and a higher-order construct other than the latter was 0.899 (resource efficiency–GM) and the highest between dimensions of different constructs was 0.887 (energy-saving technologies–pollution prevention) with both being below 0.90. Ratios involving a higher order construct and its respective dimensions or among dimensions of a same construct should be high and should not be regarded as a violation of discriminant validity. The LT-ES ratio (0.898) is near the threshold, an indicator of the conceptual similarity of lean and environmental goals, and is recognized as one of the limitations.

Table 6. Discriminant validity: heterotrait–monotrait ratio (HTMT)

	ES	GM	LT	et	gt	lb	lc	lp	ls	pp	re	rm
ES												
GM	0.866											
LT	0.898	0.827										
et	0.857	0.853	0.780									
gt	0.852	0.851	0.813	0.896								
lb	0.836	0.788	0.871	0.745	0.768							
lc	0.696	0.853	0.684	0.765	0.676	0.675						
lp	0.896	0.833	0.861	0.780	0.802	0.843	0.692					
ls	0.816	0.814	0.862	0.772	0.827	0.831	0.644	0.875				
pp	0.867	0.805	0.804	0.887	0.874	0.764	0.640	0.796	0.809			
re	0.881	0.899	0.826	0.859	0.859	0.846	0.700	0.830	0.856	0.865		
rm	0.873	0.877	0.765	0.837	0.804	0.719	0.779	0.790	0.746	0.805	0.876	

Note: ES, GM and LT are the higher-order constructs; lowercase codes denote first-order dimensions (See table 1). Threshold: HTMT < 0.90 [21].

Structural Model: Collinearity and Path Coefficients

The predictor constructs were not highly correlated; for the LT → GM path, the VIF was 1.000 and for the two predictors of ES, the VIFs were 2.741, which is well below the conservative limit of 3.3. Table 7 presents the path coefficients, significance and effect sizes.

Table 7. Structural model: direct effects and hypothesis testing

Hypothesis	Path	β	Sample mean	SD	t-value	p-value	f^2	VIF	Decision
H1	LT → ES	0.376	0.378	0.069	5.415	< 0.001	0.392	2.741	Supported
H2	LT → GM	0.797	0.795	0.052	15.331	< 0.001	1.741	1.000	Supported
H3	GM → ES	0.603	0.600	0.070	8.624	< 0.001	1.002	2.741	Supported

Note: β = standardised path coefficient; SD = bootstrap standard deviation; f^2 effect size thresholds: 0.02 small, 0.15 medium, 0.35 large [19].

H1: lean thinking has a positive and significant direct effect on environmental sustainability ($\beta = 0.376$, $t = 5.415$, $p < 0.001$) with a large effect size ($f^2 = 0.392$) is supported by the results. This suggests that, in spite of controlling for green manufacturing, lean behaviours, procedures and skills have an immediate impact on resource efficiency and pollution prevention.

H2 is also supported. Lean thinking has the strongest effect in the model, on green manufacturing ($\beta = 0.797$, $t = 15.331$, $p < 0.001$; $f^2 = 1.741$). This shows that lean thinking is the key factor that drives green manufacturing capability in the factories studied, with the lean one standard deviation being correlated with the green manufacturing one standard deviation as close as 0.80.

H3 is supported as well: green manufacturing has a positive and significant effect on environmental sustainability ($\beta = 0.603$, $t = 8.624$, $p < 0.001$) with a large effect size ($f^2 = 1.002$). Hence, the direct effect of lean thinking is not as significant as the direct effect of green manufacturing, which is the best prediction of environmental sustainability.

Figure 3 indicates that all the structural paths are positive and significant. The strongest path is the one between lean thinking and green manufacturing, followed by the one between green manufacturing and environmental sustainability. The third structural path, that between lean thinking and environmental sustainability, is the weakest of the three but still strong. The second order loadings indicated inside the construct boxes show that each dimension is a good representation of the higher order construct.

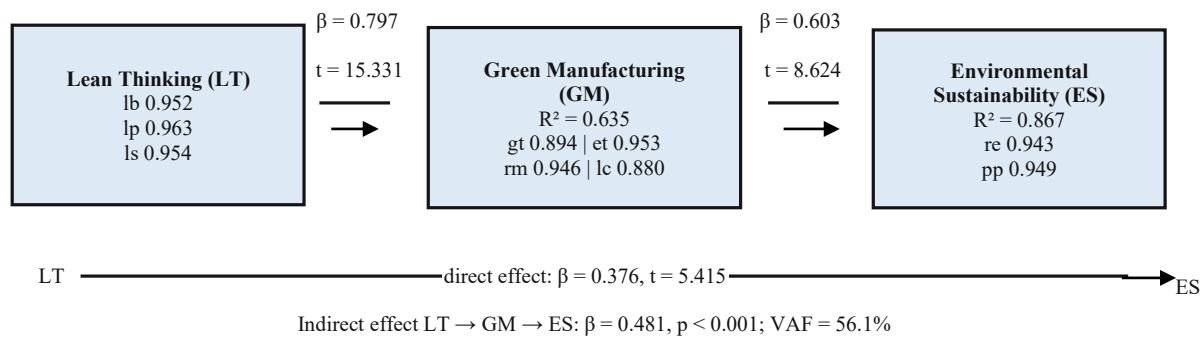


Figure 3. Estimated structural model (Standardised path coefficients, t-values, R² and second-order loadings)

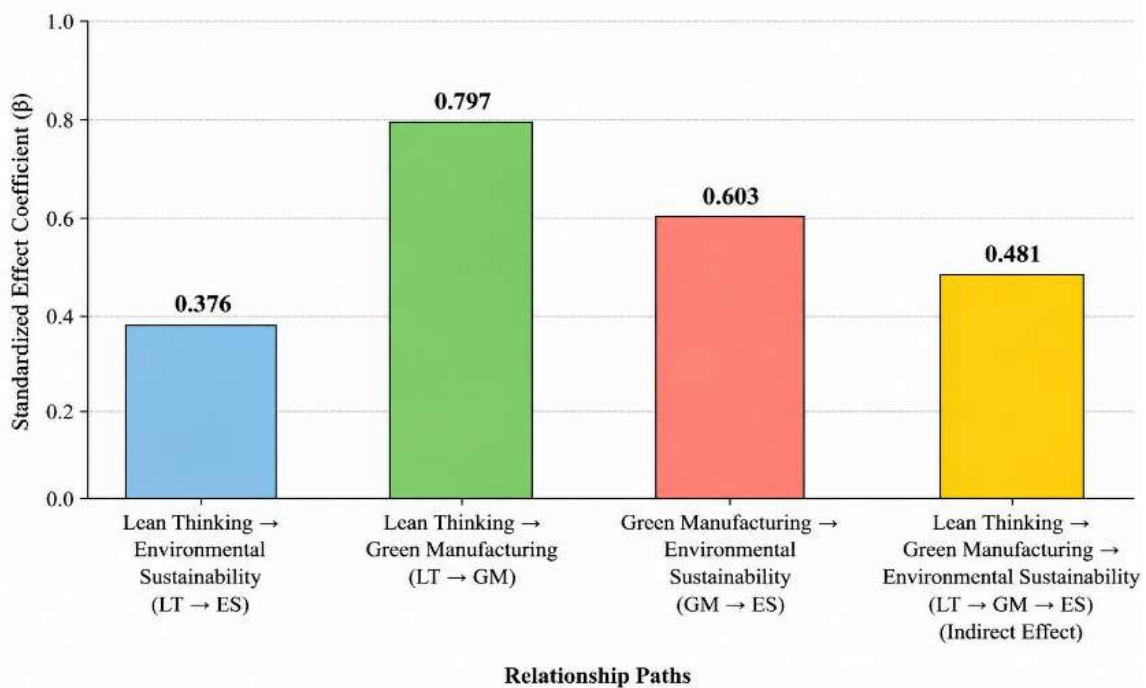


Figure 4. Comparative analysis of structural path effects in the lean–green sustainability framework

Figure 4 shows the standardized path coefficients (β) of the PLS-SEM model proposed, which illustrates the direct and indirect linkages between lean thinking, green manufacturing, and environmental sustainability. From the results, it is clear that the strongest impact exists from lean thinking to green manufacturing, followed by green manufacturing to environmental sustainability.

Explanatory Power, Predictive Relevance and Model Fit

Table 8 presents the explanatory and predictive ability of the model. Lean thinking accounts for 63.5% of the variability in green manufacturing ($R^2 = 0.635$; adjusted $R^2 = 0.633$), which is a moderate-to-high degree of variability, while lean thinking and green manufacturing combined account for 86.7% of the variance in environmental sustainability ($R^2 = 0.867$; adjusted $R^2 = 0.865$), which is high, based on the 0.25/0.50/0.75 criteria. The value of Q^2 of environmental sustainability at 0.365 is greater than zero and signifies moderate-to-high predictive relevance. The SRMR of 0.077 is less than the 0.08 critical value, signifying acceptable fit. The very high R^2 of environmental sustainability needs to be interpreted cautiously, as explained in Section 5.5.

Table 8. Explanatory power, predictive relevance and model fit

Endogenous construct	R ²	Adjusted R ²	Q ²	Explanatory level
Green Manufacturing (GM)	0.635	0.633	—	Moderate to substantial
Environmental Sustainability (ES)	0.867	0.865	0.365	Substantial
Model fit: SRMR = 0.077 (threshold < 0.08)				

Note: R² benchmarks 0.25 weak, 0.50 moderate, 0.75 substantial; Q² > 0 indicates predictive relevance; Q² is reported for the final target construct (ES) [19].

Mediation Analysis

Table 9 provides the results of the mediation analysis. The specific indirect effect of lean thinking on environmental sustainability via green manufacturing is positive and significant ($\beta = 0.481$, SE = 0.064, $t = 7.516$, $p < 0.001$; 95% CI [0.356, 0.606]) in favor of H4, given that the confidence interval excludes zero. Since the direct effect of lean thinking on environmental sustainability is also positive and significant ($\beta = 0.376$) and both effects have the same signs, it is a complementary partial mediation. The total effect of lean thinking on environmental sustainability is 0.857 (0.376 + 0.481), and VAF is 56.1% (0.481/0.857), falling into the 20-80% interval of partial mediation. To sum up, more than 50% of the total effect of lean thinking on environmental sustainability passes through green manufacturing.

Table 9. Mediation analysis: direct, indirect and total effects

Effect	Path	β	t-value	p-value	95% CI	Result
Direct effect	LT → ES	0.376	5.415	< 0.001	[0.241, 0.511]	Significant
Indirect effect (H4)	LT → GM → ES	0.481	7.516	< 0.001	[0.356, 0.606]	Significant; H4 supported
Total effect	LT → ES	0.857	19.887	< 0.001	[0.807, 0.895]	Significant
VAF = indirect/total = 0.481/0.857 = 56.1%; mediation type: complementary partial mediation						

Note: CI = 95% confidence interval. Direct effect: $\beta \pm 1.96 \times$ bootstrap SD. Indirect effect: standard error obtained with the delta method from the bootstrap SDs of the LT → GM and GM → ES paths. Total effect: equal to the LT–ES correlation in this single-mediator model, tested with Fisher's z transformation ($n = 145$). VAF = variance accounted for (< 20% no mediation, 20–80% partial, > 80% full mediation).

DISCUSSION

Discussion of Findings

The findings reveal that lean thinking is indeed a pivotal determinant of environmental sustainability in Najaf's garment factories, and a considerable extent of its impact is mediated by green manufacturing. The strongest association in the model – between lean thinking and green manufacturing ($\beta = 0.797$) – shows that garment factories characterised by higher development of lean processes and skills are the ones that use more green manufacturing methods and technologies. This aligns with the understanding of lean as an accelerator of greening [4], because with standardisation and transparency of business processes, environmental waste becomes visible, and the problem-solving skills of the employees make it easier to incorporate green technologies.

The large influence of green manufacturing on sustainability ($\beta = 0.603$) means that the internal green capabilities have direct influence on resource efficiency and prevention of pollutions in accordance with evidence of improvement of sustainability through green manufacturing [14]. The positive influence of lean thinking on environmental issues ($\beta = 0.376$) suggests that waste reduction leads to environmental gains such as reduction of defects, overproduction, and material handling without any additional investment for green capabilities [11] [13]. Finally, the complementarity partial mediation (indirect effect 0.481; VAF 56.1%) indicates that the highest environmental gain from lean thinking is achieved

when lean is supported by green manufacturing: lean alone provides some part of the gain, while more than 50% of the total gain occurs due to green manufacturing capabilities.

Comparison with Previous Studies

Table 10 presents the comparison of current findings with the findings from previous research on lean-green sustainability. It can be observed that the directions of the relationship obtained from Najaf's clothing manufacturing firms are consistent with the international literature, although the model suggested here differs from existing models in three aspects.

Table 10. Comparison of the present findings with previous lean–green studies

Study	Context and method	Key finding	Comparison with present study
Yang et al. [7]	309 international manufacturers; covariance-based SEM	Prior lean experience positively related to environmental management practices, which acted as a mediating variable	Consistent: an environmental practice construct (here GM) mediates the lean effect
Hajmohammad et al. [8]	Manufacturing plants; survey-based SEM	Lean management fosters environmental practices, which improve environmental performance	Consistent with H2 and H3
Inman and Green [9]	182 U.S. manufacturing managers; SEM	Lean directly affects environmental performance, but the indirect effect through green practices is stronger (complementarity)	Same pattern: indirect effect (0.481) exceeds direct effect (0.376)
Awan et al. [17]	250 Pakistani manufacturing firms; SEM (AMOS)	Green supply chain management mediates the effect of several lean bundles on sustainable performance	Consistent; present study uses an internal, factory-level mediator instead of a supply-chain mediator
Belhadi et al. [5]	Manufacturing companies in North Africa; empirical survey	Lean Six Sigma and green manufacturing, integrated with big data analytics, improve environmental performance	Consistent; present study adopts its four-dimension GM framework and confirms it in apparel manufacturing
Pampanelli et al. [13]	Production cells of an international engineering corporation; case study	Lean & Green Model reduced resource use by 30–50% on average	Survey evidence at factory level supports the same lean-to-resource-efficiency mechanism
Present study	145 employees, Iraqi apparel factories; PLS-SEM with higher-order constructs	LT → ES $\beta = 0.376$; LT → GM $\beta = 0.797$; GM → ES $\beta = 0.603$; indirect $\beta = 0.481$ (VAF 56.1%); $R^2(\text{ES}) = 0.867$	Extends prior models to lean thinking (behaviours, procedures, skills) and internal GM capabilities in a new sector and region

Three conclusions arise from the comparison. First, the emphasis on the indirect effect over the direct one is similar to the complementarity found by Inman and Green [9], in an entirely different context, thereby increasing the external validity of the lean–green complementarity hypothesis. Second, while Yang et al. [7] and Awan et al. [17] used mediating variables such as environmental management or supply-chain practices, the current research demonstrates that green manufacturing capabilities play the same mediation function, which is more practical for the factory manager. Third, by considering lean not as a tool but as a mindset, the model considers the behavioral and skills components of lean, which are deemed important for the environmental performance by recent qualitative studies [10]. The strong explanatory power of the model ($R^2 = 0.867$ for environmental sustainability) suggests that the lean thinking-green manufacturing framework explains most of the variance in the perception of environmental sustainability in the sampled factories.

Theoretical Implications

In three different ways, this study makes a contribution to lean–green theory. First, this study clearly explains and empirically verifies the process by which lean thinking influences environmental sustainability, by demonstrating that green manufacturing plays the role of a complementary partial mediator instead of a substitute for lean. Second, this study proves that capability building process in the resource-based view helps understand the relationship between lean and green, where lean thinking is an important and intangible capability that improves the absorptive capability for green technologies, thus influencing the environment. Third, the higher order specification reveals that all the dimensions of lean behaviors, processes, and skills, and the four dimensions of green manufacturing capability, strongly measure their constructs (loadings 0.880–0.963).

Practical Implications

For apparel factory managers, the implications of the study mean that lean and green initiatives should be combined rather than run as separate activities. Given that lean practices scored the lowest, development of a culture of continuous improvement, for instance kaizen workshops, visual management, and employee suggestion systems, would have to come first because of its importance for both lean and green operations. Lean activities such as value stream mapping need to be broadened to encompass mapping of energy, water and material flows so that waste of an environmental nature as well as traditional waste would become known. Training programs would need to incorporate both lean problem solving and maintenance of energy-efficient and reconfigurable machinery. Life cycle management, the area with the poorest measurement properties, deserves special focus, for instance by means of using fabric cut-offs and recycling of packaging. For policy makers in the Iraqi Ministry of Industry and Minerals, the implications of the study mean that support for lean training and adoption of green technology needs to be coordinated because the pay-off is greatest when both are present.

Limitations

Some limitations need to be pointed out. First, this study is limited to cross-sectional, subjective perceptions gathered from a single sample population in one governorate alone, making any causal claims impossible and rendering the study externally invalid and prone to common-method bias. Second, the measure of environmental sustainability is completely dependent on subjective perceptions of employees and not on any objective measures (energy used for each piece of clothing or amount of waste) [25]. The life cycle management factor had an AVE lower than 0.50, and some composite reliabilities exceeding 0.95 point to item redundancy. Moreover, the extremely high composite reliability figures found in the case of higher-order constructs, namely Lean Thinking (0.970) and Green Manufacturing (0.964), clearly suggest item redundancy and structural collinearity of the indicators. The overlap in variance between the items leads to an exaggerated value of the reliability coefficient. Therefore, future revisions of the scale should involve a process of item purification, whereby redundant wording is eliminated and fewer indicators per construct are considered.

CONCLUSION

The study was carried out to determine the influence of lean thinking on environmental sustainability, mediated by green manufacturing within the apparel factories in Najaf, Iraq, using PLS-SEM analysis of data collected from 145 employees. The measurement model had good reliability and validity, having composite reliability of 0.801–0.970, and HTMT ratios less than 0.90. There are four major findings. First, the three constructs had been rated to be at high level (RII 0.769–0.789), with the pollution prevention being the most significant dimension while lean behaviors was least significant one. Second, the influence of lean thinking on green manufacturing was strongly significant ($\beta = 0.797$, $p < 0.001$), explaining 63.5% of the latter. Third, green manufacturing ($\beta = 0.603$, $p < 0.001$) and lean thinking ($\beta = 0.376$, $p < 0.001$) were influencing the environmental sustainability directly, accounting for 86.7% of the former variance with sufficient predictive relevance ($Q^2 = 0.365$) and model fit (SRMR = 0.077). Fourth, the green manufacturing was partially mediating the relation of lean thinking and environmental sustainability (indirect effect $\beta = 0.481$; VAF = 56.1%). The implications of the current findings relate

to demonstrating that lean thinking and green manufacturing complement each other and are not mutually exclusive options; lean thinking creates the culture and process discipline needed for the development of green manufacturing capability, and more than 50% of its positive impact on the environment comes from the capability. Thus, lean-green approach is a viable path to environmental sustainability for apparel manufacturers in developing countries. For future research, there are several possible ways to extend this study.

Conflict of Interest Statement

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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