Journal of Scientific & Industrial Research
Vol. 85, February 2025, pp. 123-135
DOI: 10.56042/jsir.v84i02.9775

Life Cycle Energy Assessment of Rajasthan's Marble Processing Plant for Sustainable Environment Planning

Dharmanshu Singh Sodha[1], Harlal Singh Mali[1] & Amit Kumar Singh[2]*

[1]Department of Mechanical Engineering, Malaviya National Institute of Technology Jaipur, Jawahar Lal Nehru Marg, Jaipur 302 017, Rajasthan, India

[2]Department of Mechanical Engineering, National Institute of Technology Calicut, Kerala 673 601, India

Received 21 March 2024; revised 18 September 2024; accepted 18 November 2024

The construction sector plays a vital role in achieving sustainability; therefore, monitoring and continuous improvement in energy and environmental performance in this sector are crucial. The Rajasthan state of India contains 64% of Indian marble resources, and approximately 90% of the marble is being processed in Rajasthan alone. In past decades, the production of marble stones has been in very high volume, leading to high energy consumption. Since the processing of marble worldwide is performed by Small-to-Medium Enterprises (SMEs), these industries lack technology, leading to low efficiency and more expensive production with significant waste generation. The objective of this study is to assess the energy consumption and environmental impacts of typical marble processing SMEs in Rajasthan and to propose strategies for enhancing production efficiency and reducing the ecological footprint. Through site surveys, power rating data were collected to quantify electrical energy usage across various operations of marble production, and further, each operating scenario's energy consumption was compiled. Environmental impacts, particularly CO_2 emissions, were quantified using the GaBi® sustainability software. This study presents a consolidate index for assessing the economic and environmental performance of different operating scenarios and for ranking processing lines for One Square Feet (ft^2) of processed marble stone, providing a comprehensive sustainability performance assessment. The findings highlight the potential for substantial environmental advantages by implementing energy-efficient practices and critical technological advancements to improve the marble processing industries' sustainability and operational efficiency, potentially assisting broader regional environmental initiatives. Eventually, the findings aim to contribute to the development of greener production practices in the sector, promoting both economic and environmental sustainability.

Keywords: Carbon footprint, Energy efficiency, Life cycle impact, Resource optimisation, Sustainability index

Introduction

Rajasthan, a prominent Indian state, is known for its extensive marble reserves, used in various applications, including construction, cladding, and artwork. The marble industry's decorative and durable nature has made it a key contributor to the state's economic growth. Rajasthan holds 90% of India's marble stone deposits,[1] with significant annual production levels averaging over 10 million tons in recent years.[2–5] The high energy demands of marble processing, primarily powered by fossil fuels, result in considerable carbon dioxide (CO_2) emissions, contributing to global climate change. Thus, improving the sustainability of the marble processing industry is crucial.

Several studies have been carried out on sustainability of industrial processes. Gazi *et al.*[6] provide a rigorous methodology to assess the current environmental circumstances of a typical European SME operating in the marble quarrying and processing industries. Greece generates electricity from lignite resources, which account for eighty percent of sulphur dioxide emissions. According to Kaldellis *et al.*[7], natural gas replaces lignite for electricity production as a desulfurizer in Greece's electricity production. To increase global sustainability, all countries that engage in the stone quarrying and processing industries should do comparable energy assessments. In Perlato di Sicilia, Traverso *et al.*[8] evaluate the energy and environmental performance of the typical Sicilian marble industry. Data obtained from the sector were analysed using the Life Cycle Assessment (LCA) method. Alqadi *et al.*[9] conducted a comparative analysis of the life cycle energy consumption and emissions associated with natural and artificial stones, highlighting the lower impact of natural stones. Liguori *et al.*[10] conducted comprehensive energy and environmental audits of marble manufacturing plants in

---

*Author for Correspondence
E-mail: amitsingh@nitc.ac.in

the Custonaci basin, identifying significant ecological impacts. The study suggested a recommendation for reducing waste that harms the environment. The significant environmental effects of industrial CO_2 emissions are climate change and ecological stability. As a concern of the European Union and the Italian national government, Capitano *et al.*[11] observed the Custonaci Italian Marble Production area and proposed strategies to preserve energy resources to avoid environmental consequences. According to the author, the marble production industries have a very significant potential for improvement. Furthermore, de Toldi and Pestre[12] emphasise the significance of natural stone within low-carbon building strategies, promoting sustainable practices in the stone industry. In the Middle East and North Africa, Hanieh *et al.*[13] has investigated the environmental, economic, and social effects of the marble industry. The author has proposed the 3R principle, demonstrating the best utilization of energy, water, and natural marble. The research employed the doughnut modelling technique to show how production and consumption are related. Gabbrielli *et al.*[14] inspected the technical and economic factors of reducing energy use in the paper industry and analysed the sector's long-term stability. Shu *et al.*[15] published parameters of the processing series, the power utilization needed for ceramic tile manufacturing, and a cleaner manufacturing technique, while Fattahi and Ghaedi[16] utilised the rock engineering system to forecast energy consumption precisely. Nicoletti *et al.*[17] conducted an LCA comparison of ceramic with marble tiles to analyse their respective environmental profiles. The study also examined the major energy requirements for creating a typical Italian marble tile. Konstantopoulou *et al.*[18] evaluated the installation of the ISO 14001 environmental management system and the potentials for energy conservation in the mining industry of northern Greece. Another environmental study was conducted between Greek marble and granite production by Taxiarchou *et al.* .[19] They conducted an LCA that only examined water and energy usage. Torricelli *et al.*[20] conducted an LCA on the Italian Pietra Serena sandstone quarried in the Tuscan districts of Firenzuola, Ascoli, and Trasimeno. However, the study was based on input flows of water and energy supplies, while impacts related to cutting tools were hardly even considered, most likely due to a lack of data. Catarino *et al.*[21] conducted an economic and environmental analysis and provided a complete list of used raw materials, water, energy, products, waste, and noise emissions but did not quantify them. Finally, Atici *et al.*[22] investigated the effectiveness and energy usage of cutting methods.

Even though Rajasthan produces an immense amount of marble stone products, there is a scarcity of literature related to the energy consumption of the marble processing industry. Therefore, the aim of the study is to presents the energy assessment of the techniques employed in Rajasthan's marble processing industry. The scope of the research includes analysing the energy consumption associated with marble production processes, from marble block processing to the final marble products. It evaluates environmental impacts, particularly CO_2 emissions, and proposes strategies for enhancing energy efficiency. The survey was conducted in the Rajasthan's marble processing industry and energy consumption and time taken for each operation was collected. Using an energy audit approach, the study performed the energy assessment and the ecological effect of standard marble products' processing chains. The methodology used is based on identifying energy-intensive marble production processes in a plant, the assessment of energy consumption per square feet of marble product, and calculation of CO_2 emissions with the help of the sustainable tool Gabi®, and further calculation of Consolidate Index (ECM) of economic and environment performance to manufacture one ft^2 of marble product. This study further aims to propose recommendations for enhancing production efficiency and minimizing the ecological footprint of marble processing industries, consequently contributing to cleaner manufacturing in the industry.

Case Description and Methodology

Case Description: Rajasthan's Processing Plant

The proposed study is based on Marble processing industries in the Indian state of Rajasthan. The operational features and power rating of each machine used in the processing industry is provided in the study. The processing plants are standard SMEs within the marble manufacturing sector, defined by their equipment, processing machines, techniques, and economic scale.

Overview and Operations of the Marble Processing Plant

Most of the SME marble processing industries in Rajasthan operate in Kishangarh and Jalore, located 60 to 238 kilometres from the quarrying sites. The plant layout and power ratings of the installed equipment are illustrated in Figs. 1 and 2, respectively.

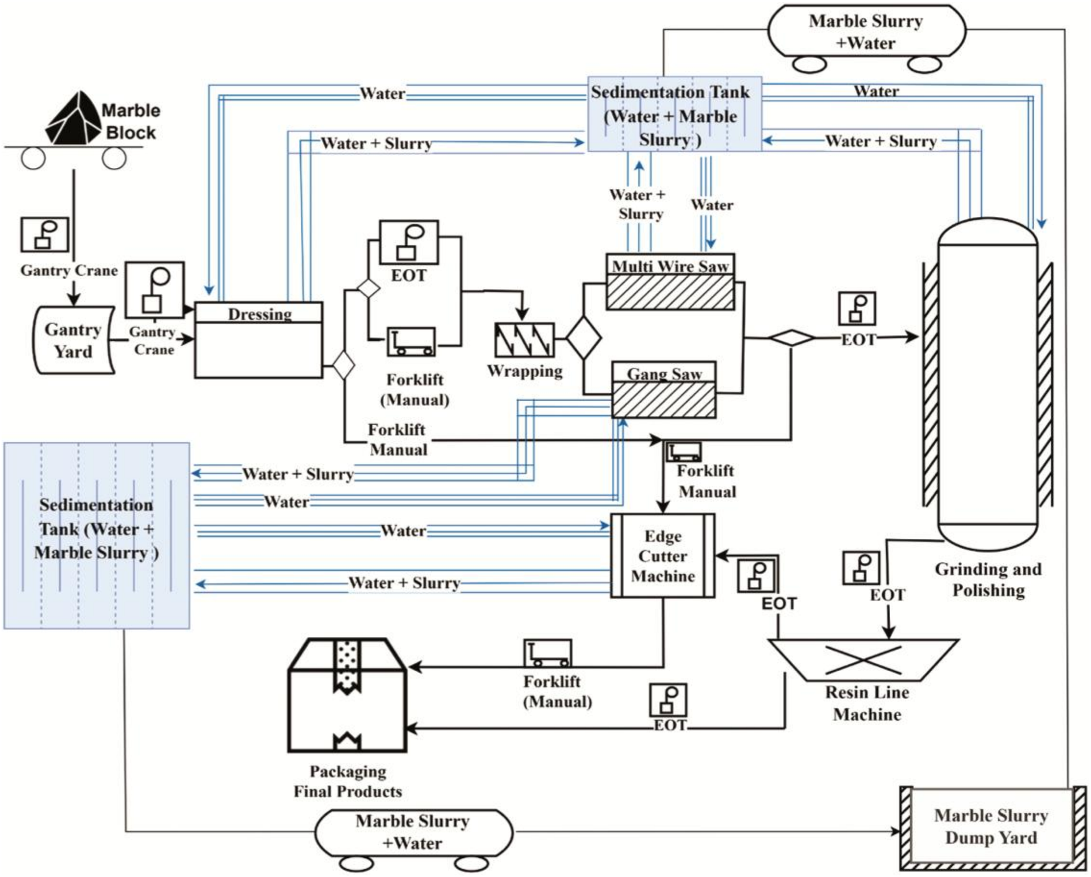

Fig. 1 — Typical Rajasthan marble processing plant layout

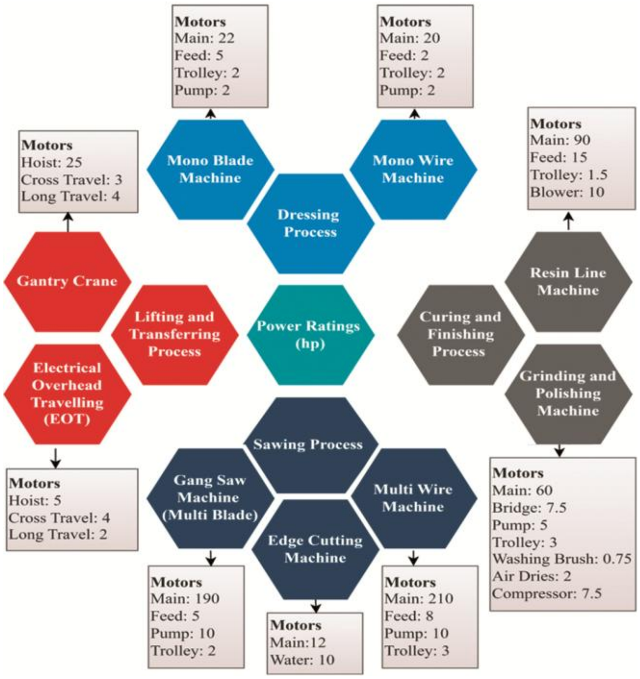

Fig. 2 — Equipment installed in the marble processing industry, along with their power ratings

Three main categories of machines are used in the Rajasthan's marble industry: cutting, finishing, and auxiliary machines. Cutting equipment includes diamond mono-wire, mono-blade, multi-blade gang saw, multi-wire, and edge-cutting machines. Finishing involves resin line machines, grinding, and polishing machines. Auxiliary equipment such as gantry cranes and Electric Overhead Traveling (EOT) machines handles the internal transport of marble blocks and slabs between different processing machines.

Energy Assessment Methodology

An approach that can detect, define, estimate, and analyse energy flows in marble stone processing plants is required to evaluate energy-saving potentials. This type of method is expected to result in higher accuracy levels. To figure out the total energy inputs, the chosen method takes into account the details of the processing sequences and the machinery needed to make the marble stone product (a slab or tile). The specification of the product is the initial phase. As shown in Table 1, the marble stone processing industries use various combinations of processing

Table 1 — Machining combinations for several operation scenario

S.No	Categories →	Auxiliary machines		Cutting machines					Finishing machines	
	Process →	Transferring		Dressing		Sawing			Polishing and Curing	
	Products ↓	Gantry-crane	EOT	Mono-blade	Mono-wire	Gang-saw	Multi-wire	Edge-cutting	Resin-line	Grinding/ Polishing
1	Unpolished tiles	×	×	×	—	×	—	×	—	—
2	Unpolished tiles	×	×	—	×	×	—	×	—	—
3	Polished tiles	×	×	—	×	—	×	×	×	×
4	Polished tiles	×	×	×	—	—	×	×	×	×
5	Unpolished slab	×	×	×	—	×	—	—	—	—
6	Unpolished slab	×	×	—	×	×	—	—	—	—
7	Polished slab	×	×	—	×	—	×	—	×	×
8	Polished slab	×	×	×	—	—	×	—	×	×

machines to create the final product (slabs or tiles). The second phase is to measure the power usage of individual processing machine in the marble stone processing industry in order to determine how much energy each processing line consumes. This strategy compares how much energy each processing line needs to make the final marble products. The energy consumption per ft^2 of marble product for each machine was calculated based on its nominal power, with data gathered from the literature and supervisors working in the Rajasthan's stone processing industry. Efficiency losses due to regular wear and tear have not been addressed; as such the measured energy levels represent an upper limit. This paper's methodology is extendable and applicable to similar small and medium-sized industries.

Energy Consumption Calculation

Each processing machine in the marble processing industry operates through numerous steps to process one ft^2 of marble stone. For each step, the respective motor's power rating was obtained through consultations with industry supervisors. Additionally, the operational duration of each step was recorded during site visits to ensure accuracy. The energy consumption for each step was calculated by multiplying the motor's power rating by its operating time. The total energy consumption for each machine was then determined by summing the energy consumption of all individual steps. Detailed calculations of the energy consumption for each processing machine, corresponding to the production of one ft^2 of marble stone, are presented in the Results and Analysis section.

Sustainability Analysis Methodology (LCA and ECM)

Processing natural stones in general, and marble stone in particular, raises concern about cutting technique efficiency and environmental impacts. There are three significant concerns related to the processing industries: waste management, energy efficiency, and ecological pollution (noise, dust, disturbance to natural habitation, and gaseous and particulate emissions). This study identifies different operating scenarios, and each operating scenario's energy consumption to process one ft^2 of marble product is calculated. This research introduces a methodology for evaluating the sustainability of operational scenarios within the marble processing sector in Rajasthan. This method employs the LCA technique, utilizing the CML impact assessment method to measure and evaluate the environmental impacts of various operational scenarios in the Rajasthan's Marble Processing Industry. The analysis undertaken by the LCA focuses on quantifying the Global warming potential (GWP) CO_2 emissions, utilising the sustainability tool GaBi®. The first stage in conducting an LCA is to define the aim and scope of the analysis. After establishing these components, the processing operations of the product are outlined and explained under evaluation. Prior to conducting the LCA, it is essential to establish the context, define the boundary limits, and identify the specific environmental impacts that will be considered. The sequence of processes a product goes through, starting from its development, then its use, maintenance, and ultimately, its disposal, is commonly known as the "product life cycle". The comprehensiveness of construction product LCAs may vary, including a greater or lesser number of lifetime activities depending on the desired scope.[23] This intended level of detail specifies the boundary condition of the LCA. The boundary conditions "cradle to gate," "gate to gate," and "gate to grave" are all options for an LCA.[24] The present work covers the marble stone life cycle in the Marble processing industry (Gate to Gate boundary conditions). Finally, the environmental score was computed utilizing the Building for Environmental and Economic Sustainability (BEES) strategy.[25] Environmental scores serve as an indicator for a comprehensive evaluation of the sustainability of the different operational scenarios. The environmental score is calculated using Eq. 1.

$$\mathrm{EnvScore_i} = \sum_{k=1}^{p} \mathrm{IAScore}_{ik} \qquad \dots (1)$$

where, $\mathrm{EnvScore_i}$ is the i^{th} alternative environmental performance score and p is the number of environmental impacts categories and $\mathrm{IAScore}_{ik}$ is the alternative i^{th}weighted and normalised impact assessment score in terms of environmental impacts k. The $\mathrm{IAScore}_{ik}$ is calculated using Eq. 2.

$$\mathrm{IAScore}_{ik} = \frac{IA_{ik} \times IV_{wtk}}{Max\ \{IA_{1k}, IA_{2k} \ldots\ldots\ldots\ldots\ldots IA_{mk}\}} \times 100 \qquad \dots (2)$$

The Environmental scores is calculated for each operational scenario utilizing the previously stated equations, and subsequently, the sustainability of each processing line is assessed. Following this, an evaluation was conducted to determine the cost required for each processing line to process one ft^2 of marble product utilizing the identical framework. During the evaluation, the following equations are used to create a "consolidate index" by putting together the cost indices, the Environmental scores, and the manufacturing One ft^2 of marble product from different processing lines.[25,26]

$$ECMi = \frac{Mfg_{in}}{\mathrm{EnvScore_{\,i}} + \mathrm{Cost_{in}}} \qquad \dots (3)$$

$$\mathrm{EnvScore_{in}} = \frac{\mathrm{EnvScore_{\,i}}}{\mathrm{Max\ (EnvScore_{\,1}, EnvScore_{\,2} \ldots\ldots\ldots EnvScore_{\,m})}} \qquad \dots (4)$$

$$\mathrm{Cost_{in}} = \frac{\mathrm{Cost_{\,i}}}{\mathrm{Max\ (Cost_{\,1}, Cost_{\,2}} \ldots\ldots\ldots Cost_{\mathrm{m}})} \qquad \dots (5)$$

$$\mathrm{Mfg_{in}} = \frac{Mfg_{\mathrm{i}}}{\mathrm{Max\ (Mfg_{\,1}},Mfg_{2} \ldots\ldots\ldots Mfg_{\mathrm{m}})} \qquad \dots (6)$$

where ECM_i is the consolidate index of production, economic, and environmental performance of operational scenarios; $EnvScore_{in}$ is the normalized environmental score obtained from BEES model analysis of operational scenario i; $Cost_{in}$ is the normalized cost of operational scenario i; Mfg_{in} is the manufacturing of marble product of processing line i; and m is the number of processing lines. The provided Eqs 3–6 are utilized to simultaneously assess the environmental, economic, and manufacturing aspects of all the processing lines. This approach presents an integrated perspective by incorporating the economic and environmental impact of operational scenarios implemented within the marble processing industry in Rajasthan.

Results and Discussion

Energy Assessment

The marble block extracted from the quarry is transported to the processing plant to be transformed into finished marble products. The marble block size analysed in the study has an average volume of 360 cubic feet (10 × 6 × 6 ft^3). Mono-blade and mono-wire dressing machines square cut the marble block, which is then transferred to the sawing process with the help of auxiliary machines. A gang saw or multi-wire saw machine cut the squared block into large slabs (10 × 6 ft^2 area and 13–20 mm thickness, as per the market requirement). This way, unpolished slabs are produced. They are moved to the resin line and polishing/grinding equipment to cure and polish the slabs. An edge-cutting machine then cuts the slab into tiles based on market demand.

The calculation to carry out energy consumption by each processing techniques for producing one ft^2 of marble product is shown in Table 2–6. The energy consumption calculation for transferring marble

Table 2 — Quarrying to marble processing plant

Steps	Process	Unit	Magnitude		
1	Quarrying to processing plant distance	km	60	165	238
2	Loading truck velocity	km/h	40	40	40
3	Truck power	kW	180	180	180
4	Capacity	Marble block	1	1	1
	Total energy consumption for 360 ft^3	kWh	270	742.5	1071
	Energy consumption per ft^3	kWh/ ft^3	0.750	2.062	2.975
	Energy consumption per slab @ 80 slabs per stone	kWh/ Slab	3.375	9.281	13.387
	Energy consumption per ft^2 @ 60 ft^2 slab area	kWh/ ft^2	0.056	0.155	0.223

Table 3 — Energy consumption by gantry crane in different processes

Steps	Process (gantry yard to dressing)	Power (kW)	Operation time		Energy consumption (kWh)
			Minute	Hour	
1	Lifting the stone from gantry yard	18.65	5	0.083	1.554
2	Transferring the stone to dressing area	3	10	0.167	0.5
3	Cross motion	2.3	4	0.067	0.153
4	Putting down the stone on dressing trolley	18.65	5	0.083	1.554
	Total energy consumption (kWh)				3.762
	Total energy consumption (kWh/ft^3)	Volume of stone = 360 ft^3			0.011
	Total energy consumption (kWh/ Slab)	One stone = 80 Slabs			0.047
	Total energy consumption (kWh/ ft^2)	Slab Area = 60 ft^2			0.0008

Table 4 — Energy consumption for dressing marble stone

Steps	Process (mono-blade dressing machine)	Power (kW)	Operation time		Energy consumption (kWh)
			Minute	Hour	
1	Trolley movement under the M/c	1.5	1	0.017	0.025
2	Lifting up of trolley	3.73	0.5	0.008	0.031
4	Dressing operation	16.5	180	3	49.5
5	Water pump	1.5	180	3	4.5
6	Downward movement of trolley	3.73	1.5	0.025	0.093
7	Trolley movement outside the M/c	1.5	1	0.017	0.025
	Total energy consumption (kWh)				54.174
	Total energy consumption (kWh/ ft^2)	Slab area = 60 ft^2			0.903
Steps	Process (mono-wire dressing machine)	Power (kW)	Operation time		Energy consumption (kWh)
			Minute	Hour	
1	Trolley movement under the M/c	1.5	1.5	0.025	0.038
2	Lifting up of trolley	1.5	0.5	0.008	0.013
3	Lifting up of trolley while M/c	1.5	150	2.5	3.75
4	Dressing operation	15	150	2.5	37.5
5	Water Pump	1.5	150	2.5	3.75
6	Downward movement of trolley	1.5	1.5	0.025	0.038
7	Trolley movement outside the M/c	1.5	1.5	0.025	0.038
	Total energy consumption (kWh)				45.125
	Total energy consumption (kWh/ ft^2)	Slab Area = 60 ft^2			0.752

stones from different quarrying plant to different processing plants is shown in Table 2.

A gantry crane is used to load and unload the stone in the gantry yard, transfer it to the dressing area for squaring, and carry the dressed marble stone to the sawing place for cutting the block into slabs. Gantry cranes consumes energy to transfer the marble block from one processing machine to another inside the processing plant, and the energy consumption calculation is shown in Table 3.

An EOT crane transfers marble slabs from the sawing area to the finishing area for curing and polishing, then to the edge-cutting machine for tiling, and finally to the packaging area. The energy consumption of the EOT crane, used for internal slab transfers, is calculated similarly to that of the gantry crane. Rajasthan's marble processing industries mostly use two types of dressing machines: mono-wire and mono-blade. The energy consumption the dressing machines require to square off the marble stone coming from the quarrying site is shown in Table 4.

Rajasthan's marble processing industries use multi-wire and gang saw machines to produce slabs from the marble block. Though Multi-wire consumes less electricity and makes a smooth cut and fewer cracks while machining marble blocks than gang saw, the multi-wire machine's high cost make it a constraint for many small to medium industries to use this machine. Further, if required, Edge-cutting machinery is used to process slabs into tiles. The calculation of energy consumption of the dressing machines to square off the marble stone coming from the quarrying site is shown in Table 5.

Table 5 — Energy consumption for cutting marble block into slab/tiles

Steps	Process (Gang-saw machine)	Power (kW)	Operation time		Energy consumption (kWh)
			Minute	Hour	
1	Trolley movement under the M/c	1.5	1	0.017	0.025
2	Lifting up of trolley	3.73	0.5	0.008	0.031
3	Lifting up of trolley while M/c	3.73	360	6	22.38
4	Cutting operation	142	360	6	852
5	Water pump	7.5	360	6	45
6	Downward movement of trolley	3.73	1.5	0.025	0.093
7	Trolley movement outside the M/c	1.5	1	0.017	0.025
	Total energy consumption (kWh)				919.554
	Energy consumption/slab (kWh/Slab)		1 Stone = 80 Slab		11.494
	Total energy consumption (kWh/ ft^2)		Slab area = 60 ft^2		0.192
Steps	Process (multi-wire saw machine)	Power (kW)	Operation time		Energy consumption (kWh)
			Minute	Hour	
1	Trolley movement under the M/c	2.24	1	0.017	0.037
2	Lifting up of trolley	6	0.5	0.008	0.05
3	Lifting up of trolley while M/c	6	270	4.5	27
4	Cutting operation	156.5	270	4.5	704.25
5	Water pump	7.5	270	4.5	33.75
6	Downward movement of trolley	6	1.5	0.025	0.15
7	Trolley movement outside the M/c	2.24	1	0.017	0.037
	Total energy consumption (kWh)				765.275
	Energy consumption/slab (kWh/Slab)		1 Stone = 80 Slab		9.566
	Total energy consumption (kWh/ ft^2)		Slab area = 60 ft^2		0.159
Steps	Process (edge cutting machine)	Power (kW)	Operation time		Energy consumption (kWh)
			Minute	Hour	
1	Cutting operation	9	20	0.333	3
2	Water pump	7.5	20	0.333	2.5
	Total energy consumption (kWh)				5.5
	Total energy consumption (kWh/ ft^2)		Slab area = 60 ft^2		0.092

Table 6 — Energy consumption in finishing the slab/tiles

Steps	Process (grinding and polishing machine)	Power (KW)	Operation time		Energy consumption (kWh)
			Minute	Hour	
1	Conveyor movement under the M/c	2.2	3	0.05	0.11
2	Up/ Down movement of heads	5.6	3	0.05	0.28
3	Cross motion of heads	5.6	3	0.05	0.28
4	Grinding and polishing operation	45	3	0.05	2.25
5	Water pump	3.7	3	0.05	0.185
6	Washing of slabs	0.75	3	0.05	0.038
7	Air drier for washed slabs	1.5	3	0.05	0.075
	Total energy consumption (kWh)				3.217
	Total energy consumption (kWh/ft^2)		Slab area = 60 ft^2		0.054
Steps	Process (resin line machine)	Power (KW)	Operation time		Energy consumption (kWh)
			Minute	Hour	
1	Slab movement to the machine	1.12	1	0.017	0.019
2	Upward movement of trolley	11.2	1	0.017	0.187
3	Curing operation	68	60	1	68
4	Blower	7.5	60	1	7.5
5	Downward movement of trolley	11.2	1	0.017	0.187
6	Slab movement back to stands	1.12	1	0.017	0.019
	Total energy consumption (kWh)				75.910
	Total energy consumption (kWh/ ft^2)		Slab Area = 60 ft^2		1.265

Cracks developed while sawing the slabs are cured by a resin line machine. After fixing the cracks, grinding is done on the slabs to reduce surface roughness, and finally, polishing on the surface is done to get a shining surface. The single machine performs grinding and polishing, with a total of 12 heads installed on a machine, in which 2 to 4 heads do grinding, and the remaining do polishing. The calculation of the energy consumption by the finishing machines to cure and polish the surface of the marble slab is shown in Table 6.

Energy consumption in marble processing is distinct across various processing stages and machinery, with each step influencing the total energy demand. Marble blocks, averaging 360 cubic feet, undergo dressing, sawing, and finishing to be processed into slabs and tiles. The calculated energy consumption data set facilitates the comparability of different techniques and strategies in any marble processing industry.

The energy consumption of eight distinct processing lines is shown in Fig. 3, indicating that lines 1, 2, 5, and 6 exhibits considerably lower energy usage than lines 3, 4, 7, and 8 due to the absence of curing and polishing steps. Industries involving surface finish operations indicate a significant rise in energy consumption, primarily due to the intensive processes of curing and polishing, which substantially raise plant energy consumption.

The proportion of energy consumption associated with each technique within eight processing lines is illustrated in Fig. 4. The dressing operations in the cutting section and the curing processes in the finishing section consume the highest energy. The results highlight the importance of targeting energy savings during the curing and polishing phases by utilising machinery in an optimised manner.

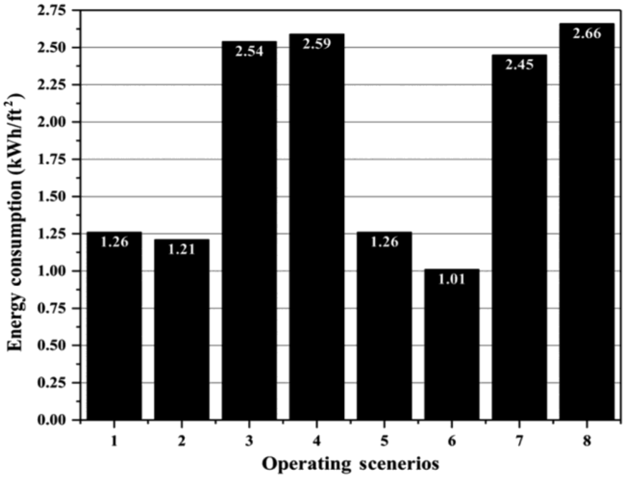

Fig. 3 — Energy consumption of processing line

Life Cycle Assessment

Aim and Scope, Boundary System and Assumptions

This study aims to analyse the marble processing industry in Rajasthan to evaluate its energy and environmental performance. The goal of the study is to determine the GWP (CO_2 emissions) of the different operating scenarios in the Rajasthan's marble processing industry. Life cycle assessment is implemented for marble stone products in accordance with ISO 14040/44.(27) The assessment was conducted using a "gate-to-gate" boundary framework, which considered the effects concerning the energy consumption for each processing line in Rajasthan's marble processing industries. The system boundary is illustrated in Fig. 3. The Rajasthan's marble processing industries consists of three primary operations: transferring and carrying the marble blocks and slabs, cutting marble stones, and finishing and curing the marble slabs.

The subsequent assumptions have been taken:

- A functional unit has been defined as one ft^2 of marble stone, representing the surface area of a marble product.
- The energy consumption per ft^2 of marble product for each technique was calculated based on its nominal power.

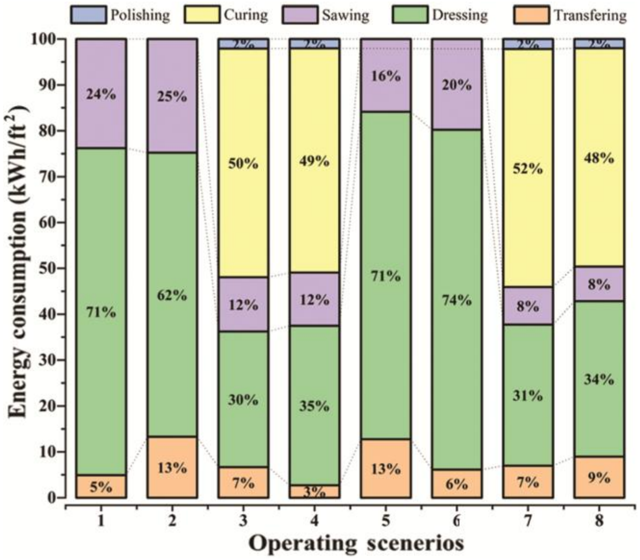

Fig. 4 — Percentage of energy consumed by each process for all 8 operating scenarios

- Each technique's maximum operational time was considered in assessing each processing line's energy consumption.
- The processing and transportation of marble stone have been evaluated in accordance with the LCA outlined in ISO 14040/44.

The operational scenarios considered in the study are the different processing lines being used to process marble stone into the final marble product in the Rajasthan's marble processing industries. The nominal power of each processing technique in the processing units is known, and the values of inputs in the form of energy consumption are determined. The present study has opted to quantify energy consumption in kWh per ft^2 of marble product.

Impact Assessment and Interpretation

This part examines the potential environmental consequences of energy consumption resulting from the processing techniques in the Rajasthan's marble processing industries. The Life Cycle Impact Assessment (LCIA) Centre of Environmental Science, Leiden (CML)-IA baseline midpoint method, also known as the problem-oriented approach, is employed in the impact assessment methodology. GWP considered in the study is taken as an environmental impact. GWP is one of the environmental impacts resulting from the emission of greenhouse gases into the atmosphere. These gases primarily enhance the average global temperature by reflecting and entrapping part of the heat emitted by the Earth's surface, such as infrared reflection of solar radiation. According to the Environmental Protection Agency of the United States, GWP is associated with various EIs, including polar ice melting, soil moisture loss, forest loss, and changes in wind and ocean flow. The GWP is the sum of the emissions of CO_2 and other greenhouse gases (N_2O, CH_4 and CO) into the atmosphere. A kilogram of CO_2 equivalent is used to measure the effect of GWP.

The estimated CO_2 emissions for each processing line, as determined with the help of the sustainability tool Gabi® is shown in Fig. 5. Carbon emission of all 8 scenarios varies from 1.04 to 2.74 kg CO_2 per ft^2 of marble tiles. This is comparable to the level of about 0.79 CO_2 per ft^2 for standard Greek marble tiles.[6] The increased CO_2 emissions relative to the Greek marble processing sector are due to the use of power from the grid, and most of India's grid power comes from coal plants, which produce a lot of CO_2 gases. Increased carbon emissions in operating scenarios 3, 4, 7, and 8 are due to the cutting operation (Multi-wire machine) and curing operations (Resin line machine). Processing lines 1, 2, 6, and 7 emit relatively low CO_2, as these processing lines use Multi-blade gang saw machines, which consume relatively low electricity compared to multi-wire cutting machines. The cracking of marble stone in the gang saw machine is higher than that of the multi-wire saw machine.

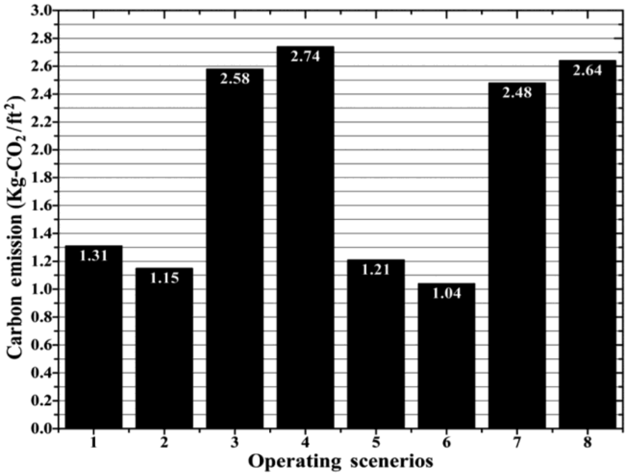

Fig. 5 — CO_2 emission of each processing line

The identified energy consumption patterns and environmental impacts in the marble processing industry offer significant insights for stakeholder decision-making. Analysing the differences in energy consumption among various processing lines enables industry managers to focus investments on more efficient technologies and processes. Processing lines exhibiting reduced energy consumption and CO_2 emissions, specifically lines 6, 2, 7, and 3, should be utilized as benchmarks for the specified marble products. Implementing the best practices identified in these more efficient processing lines enables other facilities to decrease operational costs and environmental impacts substantially. These findings assist policymakers in developing specific regulations and encouragements to enhance energy efficiency and sustainability in the sector. Promoting the use of energy-efficient technologies meets sustainability objectives and improves the competitiveness of the marble processing industry in an increasingly competitive marketplace.

Economic Analysis and Consolidate Index

The basis of the analysis is based on the expenditures linked to the processing of a one ft^2 of marble product in different processing lines. The analysis includes raw material costs, power consumption, and transportation costs. A thorough economic study of operating scenarios is conducted, considering factors such as cutting blade, diamond segments, maintenance, labour, power consumption, and transportation expenses. The results of this analysis have been compiled in Table 7. This analysis is based on the expenses to process one ft^2 of marble product.

Cost analysis of processing lines indicates that energy and raw material costs are the main expenditures. Processing lines 3, 4, 7, and 8 show higher raw material costs, obtaining 48%, while lines 2 and 6 report significant energy costs exceeding 50%.

The consolidate economic and environmental performance index, determined for each processing line, provides a comprehensive financial and environmental sustainability perspective. The maximum consolidate index value is achieved by processing line 6, which produces unpolished slabs, as shown in Table 8, signifying greater economic and environmental performance relative to the other processing lines. Similarly, processing lines 2, 3, and 7 shows favourable consolidate index values for the production of unpolished tiles, polished tiles, and polished slabs, respectively. The analysis highlights the financial impacts of energy usage and establishes a methodology for enhancing production efficiency by prioritising lines that exhibit a superior sustainability index.

Recommendations

The study revealed that polished marble products consume more electricity than unpolished ones, leading to higher carbon emissions. The prime energy-intensive processes were identified as curing (Resin Line) and the mono-blade dressing machine. Multi-wire sawing machines have higher raw material costs due to frequent wire replacements, increasing waste from diamond segments. Optimizing the removal of diamond segments from the cutting wire can minimize raw material losses and enhance efficiency. Although multi-wire machines have a higher initial cost than gang saws, their lower vibration reduces crack propagation, improving production quality. Industries should replace mono-blade with mono-wire dressing machines to reduce electricity consumption.

Solid waste management remains a significant challenge in marble processing, with slab fractures accounting for 15–20% of solid waste. The accumulation of marble fragments is typical in SME processing units. Installing crushing-pulverization units at the facility can provide a solution for reprocessing broken marble. Marble powder, a by-product of these operations, has diverse construction applications, such as cement and road building. Studies by Chavhan *et al.*[28] and Shah *et al.*[29] confirm

Table 7 — Manufacturing cost of processing lines to process one ft^2 of marble product

Processing lines	Transportation		Energy consumption		Raw material		Maintenance		Labour		Total cost
	Cost	%	Cost	%	Cost	%	Cost	%	Cost	%	INR
1	0.118	0.52	10.137	45.02	4.06	18.03	3.3	14.66	4.9	21.76	22.515
2	0.323	1.88	8.887	51.79	3.8	22.14	2	11.65	2.15	12.53	17.161
3	0.323	0.54	20.102	33.66	28.9	48.39	4.25	7.12	6.15	10.30	59.725
4	0.118	0.18	21.352	32.85	29.16	44.86	5.55	8.54	8.9	13.69	65.08
5	0.323	1.45	9.758	43.68	4.06	18.17	3.3	14.77	4.9	21.93	22.341
6	0.118	0.71	8.508	51.33	3.8	22.92	2	12.07	2.15	12.97	16.576
7	0.323	0.54	19.723	33.23	28.9	48.70	4.25	7.16	6.15	10.36	59.346
8	0.466	0.72	20.973	32.24	29.16	44.83	5.55	8.53	8.9	13.68	65.049

Table 8 — Consolidate Index of various operational scenarios

Processing Lines	$\mathrm{Mfg_{in}}$ (1 ft^2)	$\mathrm{EnvScore_{in}}$	$\mathrm{Cost_{in}}$	$ECMi$	Rank
1	1	0.478	0.346	1.213	4
2	1	0.420	0.264	1.463	2
3	1	0.942	0.918	0.538	6
4	1	1	1	0.5	8
5	1	0.442	0.343	1.274	3
6	1	0.380	0.255	1.577	1
7	1	0.905	0.912	0.550	5
8	1	0.964	0.999	0.509	7

the potential of marble powder as a supplementary cementitious material. Additionally, powdered calcium carbonate from marble waste is used in the plastics, pharmaceutical, and paper industries, enhancing product quality and reducing costs.[30] Sourcing ultra-fine particles as agricultural soil supplements or using them in construction coatings can further minimize environmental impact and lower production costs.

Water is a critical resource in marble processing, and it is used extensively for cooling and lubrication during cutting. Filtration systems, including sedimentation pits and filtration towers, are essential for recycling this water and reducing environmental impacts.[31] As demonstrated by Nasserdine *et al*.[32], improving the efficiency of water filtration systems can significantly decrease water usage and enhance the sustainability of processing plants. Noise pollution from cutting machines is another environmental concern. Prolonged exposure to high noise levels can cause health issues such as stress and cardiovascular diseases.[33] Relocating processing facilities away from urban areas and providing safety gear like noise-cancelling helmets can mitigate these risks. Effective waste management strategies are essential to address the environmental impacts of marble slurry, which contains resins and flocculants. Air pollution from slurry can cause respiratory issues, leading to diseases like bronchitis, asthma, and Chronic Obstructive Pulmonary Disease (COPD) among workers.[13,34] Implementing complete air quality monitoring and safety measures is critical for minimizing health hazards in the marble processing industries.

The stone processing industry can implement remedial measures derived from the study's findings to enhance energy efficiency and minimise environmental impacts in marble processing industries, which are listed in Table 9.

Structural changes in the organization and management of marble processing SMEs can further enhance sustainability. Installing a quality control unit combined with sales and marketing can ensure adherence to environmental norms, monitor technical advancements, and drive research and development measures. Implementing Enterprise Resource Planning (ERP) systems can streamline operations, integrating finance, manufacturing, and Customer Relationship Management (CRM) functions for improved efficiency. The findings indicate that adopting energy-efficient practices can significantly lower operational costs and carbon emissions. Upgrading technology and implementing recommended

Table 9 — Ecological effects of existing processes and suggested remedial measures

Processing operations	Ecological effects	Measures to counter impacts
Truck transportation	• Fossil consumption • Pollutant emissions	• Regular servicing of vehicle • Pollution under control certification
Cutting and finishing operations	• Waste marble block production (if block cracks while machining)	• Stone crusher installation in the centre of all processing SMEs • Trade wastes as low-grade stones or sediments
	• Energy consumption	• Use of green power sources for electricity generation • Regular monitoring of energy consumption • Processing in nominal power • Prevent frequent breaks and stops during processing • Use machinery in accordance with manufacturer guidelines. • Energy consumption comparison of comparable machining technologies
	• Waste marble slurry	• Thinning of cutting tools • Less vibrations while machining • Repairing cracks before processing the block • Install water filtrations equipment's • Utilising chemical agents for rapid water and marble dust separation
	• Dust generation	• Clean the block before cutting operation • Constant spraying of water throughout the machining operation • Masks for labours safety
	• Noise generation	• Noise cancelation helmets for workers • Proper lubrication of the cutting tool • Regular maintenance

energy-saving measures can enhance the sustainability performance of marble processing SMEs, supporting broader regional environmental goals.

However, the study encountered some limitations. The dependency on on-site surveys for energy data collection presented potential variability due to differences in reporting standards among processing industries. While motor power ratings and operational times were recorded accurately during site visits, the lack of continuous real-time monitoring limited data quality, potentially missing variations in energy consumption over time. The environmental assessment focused primarily on CO_2 emissions, excluding other critical factors like water and material usage and land degradation, which may affect the comprehensiveness of the findings. Moreover, the study was limited to small-scale marble processing units in Rajasthan, which may not fully represent more prominent industries or regions.

Future research should explore additional sustainability indicators, such as water and waste management practices, to provide a more comprehensive assessment of the impact of marble processing. Evaluating advanced cutting and polishing technologies can offer insights into improving energy efficiency. Long-term studies assessing the sustainability impacts of implemented measures can enhance our understanding of their effectiveness. Comparative analysis across different regions can also provide insights into how local conditions influence sustainability outcomes, promoting best practices across the industry.

Conclusions

The research finding quantifies the energy consumption of marble tiles, ranging from 1.21 to 2.59 kWh per ft^2 and for marble slabs, from 1.01 to 2.66 kWh per ft^2 The carbon emissions for each processing line were calculated, with values ranging from 1.04 to 2.74 kg CO_2 per ft^2 Additionally, consolidate index were calculated, revealing that processing lines 6 and 2 exhibited relatively favourable results. Implementing the suggested strategies allows marble processing plants to enhance sustainability performance, minimize environmental impact, and improve production efficiency.

The study presents several limitations. The study concentrates on a particular region, Rajasthan, and a specific industry, potentially restricting the applicability of the findings to other areas or industries. Furthermore, although energy consumption and environmental impacts were extensively examined, specific potential ecological impacts, including water and material usage, were not considered. The dependence on on-site surveys for energy data presents potential variability. Future research may broaden its focus to encompass a more comprehensive display of environmental indicators and a more extensive geographical and industrial scope, thereby improving the generalisability of the findings.

References

1 Madhavan P, *Budhpura ‘ Ground Zero’ Sandstone Quarrying in India*, (India Committee of the Netherlands) 2005.

2 GOI, *Yearbook 2018*, Ministry of Mines, Indian Bureau of Mines, vol 2018 (Government of India) 2019.

3 GOI, *Indian Minerals Yearbook 2020: Clay (others) and Shale*, Ministry of Mines, Indian Bureau of Mines, vol 2020 (Government of India) 2021.

4 GOI, *Indian Minerals Yearbook 2019*, Ministry of Mines, Indian Bureau of Mines, vol 2019 (Government of India) 2020.

5 GOI, *Yearbook 2015*, vol 2015 (Government of India) 2017.

6 Gazi A, Skevis G & Founti M A, Energy efficiency and environmental assessment of a typical marble quarry and processing plant, *J Clean Prod*, **32** (2012) 10–21, doi: 10.1016/j.jclepro.2012.03.007.

7 Kaldellis J K, Voutsinas M, Paliatsos AG & Koronakis P S, Temporal evolution of the sulphur oxides emissions from the Greek electricity generation sector, *Environ Technol*, **25(12)** (2004) 1371–1384, doi: 10.1080/09593332508618464.

8 Traverso M, Rizzo G & Finkbeiner M, Environmental performance of building materials: Life cycle assessment of a typical Sicilian marble, *Int J Life Cycle Assess*, **15(1)** (2010) 104–114, doi: 10.1007/s11367-009-0135-z.

9 Alqadi S B, Alamleh D, Naser Eldin I & Naser Eldin H, A comparative life cycle energy and greenhouse emissions of natural and artificial stone-manufacturing phase, *Results Eng*, **18** (2023) 101055, doi: 10.1016/j.rineng.2023.101055.

10 Liguori V, Rizzo G & Traverso M, Marble quarrying: An energy and waste intensive activity in the production of building materials, *WIT Trans Ecol Environ*, **108(11)** (2008) 197–207, doi: 10.2495/EEIA080201.

11 Capitano C, Peri G, Rizzo G & Ferrante P, Toward a holistic environmental impact assessment of marble quarrying and processing: proposal of a novel easy-to-use IPAT-based method, *Environ Monit Assess*, **189(3)** (2017) 108, doi: 10.1007/s10661-017-5825-6.

12 de Toldi T & Pestre T, The relevance of cut-stone to strategies for low-carbon buildings, *Build Cities*, **4(1)** (2023) 229–257, doi: 10.5334/bc.278.

13 Hanieh A, AbdElall S & Hasan A, Sustainable development of stone and marble sector in Palestine, *J Clean Prod*, **84** (2014) 581–588, doi: 10.1016/j.jclepro.2013.10.045.

14 Gabbrielli R, Medeot C & Miconi D, Energy saving in the tissue industry: Technical and economic aspects of a case study, *J Clean Prod*, **14(2)** (2006) 185–193, doi: 10.1016/j.jclepro.2004.11.001.

15 Shu Z, Zhou J & Wang Y, A novel approach of preparing press-powders for cleaner production of ceramic tiles,

J Clean Prod, **18(10–11)** (2010) 1045–1051, doi: 10.1016/j.jclepro.2010.02.001.

16 Fattahi H & Ghaedi H, Enhancing energy efficiency in stone cutting: utilizing rock engineering system method for precise maximum energy consumption prediction, *J Min Environ*, **15(1)** (2024) 345–364, doi: 10.22044/jme.2023.13409.2470.

17 Nicoletti G M, Notarnicola B & Tassielli G, Comparative life cycle assessment of flooring materials: Ceramic versus marble tiles, *J Clean Prod*, **10(3)** (2002) 283–296, doi: 10.1016/S0959-6526(01)00028-2.

18 Konstantopoulou P, Founti M & Laskaridis K, Assessment of energy saving potentials in marble quarries, in Prikyl R (Ed.), *Dimension Stone 2004: New perspectives for a traditional building material* (2004).

19 Taxiarchou M & Kostopoulou I, Life cycle analysis of dimensional stones production, *3rd Int Conf Sustain Dev Indic Miner Ind*, (2007) 169–174.

20 Torricelli M C & Palumbo E, Measuring the sustainability of the sandstone of Firenzuola: The contribution of the life cycle assessment, *1st Int Sustain Stone Conf*, (2016).

21 Catarino J, Henriques J & Maia A, Eco-efficiency in Portuguese companies of marble sector, *Int J Sustain Eng*, **9(1)** (2016) 35–46, doi: 10.1080/19397038.2015.1050479.

22 Atici U & Ersoy A, Correlation of specific energy of cutting saws and drilling bits with rock brittleness and destruction energy, *J Mater Process Technol*, **209(5)** (2009) 2602–2612, doi: 10.1016/j.jmatprotec.2008.06.004.

23 Cuenca-Moyano G M, Martín-Pascual J, Martín-Morales M, Valverde-Palacios I & Zamorano M, Effects of water to cement ratio, recycled fine aggregate and air entraining/plasticizer admixture on masonry mortar properties, *Constr Build Mater*, **230** (2020) 116929, doi: 10.1016/j.conbuildmat.2019.116929.

24 Farinha C B, de Brito J & Veiga M R, *Eco-efficient Rendering Mortars: Use of Recycled Materials*, (Elsevier) 2021, doi: 10.1016/B978-0-12-818494-3.00010-6.

25 Lippiatt B C, *BEES 2.0: Building for Environmental And Economic Sustainability Technical Manual and user Guide*, (U.S. Department of Commerce, National Institute of Standards and Technology) 2000.

26 Khodabakhshian A, de Brito J, Ghalehnovi M & Asadi Shamsabadi E, Mechanical, environmental and economic performance of structural concrete containing silica fume and marble industry waste powder, *Constr Build Mater*, **169** (2018) 237–251, doi: 10.1016/j.conbuildmat.2018.02.192.

27 European Commission-Joint Research Center, *ILCD Handbook General Guide*, (2010), doi: 10.2788/38479.

28 Chavhan J P & Bhole S D, To study the behaviour of marble powder as supplementary cementitious material in concrete, *J Eng Res Appl*, **4(4)** (2014) 377–381.

29 Shah W, Nafees M & Iqbal M, Evaluation of marble slurry waste for preparation of commercial grade cement, *J Eng Appl Sci*, **34(1)** (2015) 28–37.

30 Marras G, Bortolussi A, Peretti R & Careddu N, Characterization methodology for re-using marble slurry in industrial applications, *Energy Procedia*, **125** (2017) 656–665, doi: 10.1016/j.egypro.2017.08.277.

31 De Feo G & Ferrara C, Investigation of the environmental impacts of municipal wastewater treatment plants through a life cycle assessment software tool, *Environ Technol*, **38(15)** (2017) 1943–1948, doi: 10.1080/09593330.2016.1241306.

32 Nasserdine K, Mimi Z, Bevan B, Elian B & Elian B, Environmental management of the stone cutting industry, *J Environ Manage*, **90(1)** (2009) 466–470, doi: 10.1016/j.jenvman.2007.11.004.

33 Housley G & Burger M, Health effects of environmental noise pollution, *Australian Academy of Science*, (2017).

34 Vaishnav A & Sharma N, The study of environmental impact of marble slurry through remote sensing and GIS: A case study of Kishangarh Marble Industrial Area, *Int J Innov Res Stud*, **8(7)** (2018) 22–27.