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Environmental, Energy, and Water Footprints of Marble Tile Production Chain in a Life Cycle Perspective

Tehseen Ahmad [1], Majid Hussain [2,*], Mudassar Iqbal [3], Ashfaq Ali [4], Wajiha Manzoor [5], Hamida Bibi [6], Shamsher Ali [7], Fariha Rehman [5], Ahmad Rashedi [8], Muhammad Amin [9], Anila Tabassum [10], Ghulam Raza [11] and Dilawar Farhan Shams [1,*]

[1] Department of Environmental Sciences, Abdul Wali Khan University, Mardan 23200, Khyber Pakhtunkhwa, Pakistan; dcgistorghar@gmail.com
[2] Department of Forestry and Wildlife Management, University of Haripur, Hattar Road, Haripur City 22620, Khyber Pakhtunkhwa, Pakistan
[3] Department of Agricultural Chemistry and Biochemistry, The University of Agriculture, Peshawar 25130, Khyber Pakhtunkhwa, Pakistan; mudassariqbal@aup.edu.pk
[4] Department of Forestry, Range and Wildlife Management, Karakoram International University, Gilgit 15100, Gilgit-Baltistan, Pakistan; ashfaq_901@yahoo.com
[5] Department of Economics, COMSATS University Islamabad (CUI), Lahore Campus, Lahore 54000, Punjab, Pakistan; wajihamanzoor@cuilahore.edu.pk (W.M.); fariharehman@cuilahore.edu.pk (F.R.)
[6] Department of Soil and Environmental Sciences, The University of Agriculture, Peshawar 25130, Khyber Pakhtunkhwa, Pakistan; drhamida@aup.edu.pk
[7] Department of Soil and Environmental Sciences, Amir Muhammad Khan Campus Mardan, The University of Agriculture, Peshawar 25130, Khyber Pakhtunkhwa, Pakistan; shamsherali@aup.edu.pk
[8] College of Engineering, IT and Environment, Charles Darwin University, Casuarina, NT 0810, Australia; mabrur.rashedi@cdu.edu.au
[9] Department of Environmental Sciences, Shaheed Benazir Bhutto University, Sheringal Dir Upper 18050, Khyber Pakhtunkhwa, Pakistan; aminses123@gmail.com
[10] MM Pakistan Private Limited, Tarbela Dam, Lahore 54000, Khyber Pakhtunkhwa, Pakistan; anilatabassum.18@gmail.com
[11] Department of Biological Sciences, University of Baltistan, Skardu 16501, Gilgit-Baltistan, Pakistan; ghulum.raza@uobs.edu.pk
* Correspondence: majid@uoh.edu.pk (M.H.); drfarhan@awkum.edu.pk (D.F.S.); Tel.: +92-3088144348 (M.H.)

Abstract: The marble industry is growing in Pakistan, and Khyber Pakhtunkhwa province is the largest producer of marble tiles in Pakistan. Marble production consumes a considerable amount of water during its life cycle stages and impacts various environmental compartments, such as air, water, and soil; therefore, this study aimed to quantify the environmental impacts, water footprint, and cumulative energy demand of one-tonne marble tile manufactured in a small industrial estate Mardan (SIEM), Pakistan, and provide recommendations to improve its environmental impact profile. The study covers water consumption, energy use, and associated environmental impacts of raw materials and processes through different stages of the marble life-cycle during 2017–2018. The cradle-to-gate (extraction to factory gate or store house) life cycle assessment approach was followed in this study. The functional unit for the current study was one tonne of finished marble tile produced. Primary data from the field surveys and secondary data were modeled using the water scarcity index (WSI), CML 2000 v.2.05 methodology, and the cumulative energy demand indicator present by default in SimaPro v.8.3 software. The total water footprint required for one tonne of finished marble tile was 3.62 cubic meters per tonne (m^3/t), with electricity consumed at processing units contributing to environmental burdens the most. Similarly, electricity consumed (at processing units and during polishing) and transportation of finished marble tile to the local market were responsible for global warming potential (388 kg CO_2 eq/tonne tile), human toxicity (84.34 kg 1,4-DB-eq/tonne), freshwater aquatic ecotoxicity (94.97kg 1,4-DB eq/tonne) and abiotic depletion (7.1×10^{-5} kg Sb eq/tonne). The results of our study follow other marble tile LCA studies conducted globally (such as in Turkey and Italy), which also reported a high contribution to GWP, AP, EP, and HT due to electricity and fossil fuels consumption. The total cumulative energy demand (CED) was calculated as 5863.40 MJ (Mega Joule),

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with most energy usage associated with non-renewable fossil fuel sources. The results indicated that reducing electricity (using standard automatic machinery) and waste materials, especially paper and plastic wastes, can reduce environmental impacts. Most of the surveyed industrial units did not have wastewater treatment and recycling plants, and wastewater directly flows to nearby freshwater bodies and terrestrial ecosystems. These wastewaters should be adequately treated before being discharged into freshwater aquatic bodies. Environmental impacts must be improved by using the latest automatic machinery, reducing waste materials generation, reducing the distance between processing units and the market, and installing wastewater recycling plants.

Keywords: water scarcity index; environmental impacts; cumulative energy demand; life cycle assessment; marble; SimaPro

1. Introduction

Marble is used mainly as a construction material and primarily consists of calcite and dolomite. Limestone, schist, and granite are different rock types considered marble globally [1]. Stone and marble industries play an essential role in a country's economy as they contribute to tile production for the local construction industry. High-quality marble tiles are exported to foreign countries and provide employment opportunities; nowadays, marble is used for external buildings and internal decorations [2]. In Pakistan, marble is the sixth-largest mineral extracted [3]. In Pakistan, over 297 billion tonnes of marble reserves and more than 100 kinds of colors and varieties of m are found. The Khyber Pakhtunkhwa and Baluchistan provinces possess huge marble reserves in Pakistan [3]. Around 30 types of marbles are present in the Khyber Pakhtunkhwa province of Pakistan [4]. According to SMEDA 2006, about 1.37 million tonnes of marble and granite are produced every year, 97% of which are used locally in Pakistan [3]. Marble tiles come through different phases like extraction and cutting in the quarry, transportation of the marble from the quarry to the processing unit, cutting, resizing, and polishing the stones and tiles in the processing unit, and transportation of finished tiles to market and scraps to landfills [5]. The production chain of marble requires a considerable amount of water and energy resources. Similarly, removing the marble stones and slabs from the extraction site requires many explosives. Many waste materials are released during the manufacturing of marble production, causing various environmental impacts [5,6]. Wastewater contains many organic and inorganic pollutants like copper, arsenic, cadmium, mercury, cobalt, zinc, chromium, nickel, and lead [7]. As a result, they affect the physio–chemical properties of freshwater receiving this wastewater discharged from marble units [8]. Marble industries are one of the leading wastewater-producing production chains by which around 70% of valuable minerals in freshwater are lost through withdrawal, processing, and refining [9].

Marble industries dispose of their wastes in fine powder, which is one of the leading environmental concerns worldwide [9]. The mining process produces 40% of the marble surplus and the rock residues are dumped in adjacent infrastructures, agricultural lands, and river beds and ultimately causing environmental pollution [4]. Water scarcity is also an environmental and ecological concern as the marble life cycle requires a considerable amount of water at every stage of its production chain [9]. Workers are mostly exposed to dust particles in quarrying, grinding, and polishing processes. Marble industry workers also use contaminated water with calcium carbonate and silica; they are more likely to suffer various diseases like reparable crystalline silica, renal disease, cardiac disease, and lung cancer [4,6]. In Pakistan, the groundwater basin is the primary source of water supply in major municipalities and contributes one-third to the total water resources. Groundwater is also used in industries where industrial effluents are carried by drains to rivers and broaden the water pollution problems [10]. From 2002 to 2006, the Pakistan Council of Research in Water Resources (PCRWR) carried out a detailed work on water quality in 23 major cities in all of the country's four provinces. They concluded from their studies that around 84–89% of water resources have water quality below recommended standards set by the National Environmental Quality Standards (NEQS) of Pakistan [11].

Marble is mainly used as building material [12] and is one of the primary hotspot sources of environmental burdens in terms of energy usage and natural resource depletion [5,9,12–15]. Marble production chains, such as mining, processing, and polishing generate around 70% of waste materials [16,17], whereas quarrying produces 40% of waste in rock fragments. Most of these waste materials are discarded on nearby agricultural farms, roads, empty pits, and water bodies causing hydrospheric, lithospheric, and atmospheric pollution [18,19]; moreover, the huge quantity of water consumed during marble tile processing and turbid wastewater from marble units directly affects all types of water bodies. As there are no wastewater treatment plant facilities in the marble manufacturing units, as a result, the pollution level increases very quickly in water and soil, and consequently, adversely affects the biotic and abiotic components of the environment [7,20]. Environmental deterioration is not only severely affecting flora and fauna, but it can also affect human beings adversely; therefore, an environmental sustainability assessment of the marble tile production chain is imperative to assess and monitor the pollution level in the air, soil, and water from the marble tile production chain [6]; thus, to calculate its environmental impacts, water footprints, and cumulative energy demand, life cycle assessment (LCA) is applied, which is a recognized tool globally to assess the environmental sustainability of a product or process [21–24]. LCA estimates and assesses top-ten USA EPA most wanted environmental impacts such as global warming potential, acidification potential, eutrophication potential, abiotic depletion, terrestrial ecotoxicity, marine aquatic ecotoxicity, human toxicity, freshwater aquatic eco-toxicity, ozone layer depletion, and photochemical oxidation of a product across its life cycle stages [23–26]. While assessing the environmental impacts of a production line, LCA plays an important role in environmental policy and is also helpful in enhancing product efficiency and cost reduction [21–23]. Developed countries applied the LCA approach to their industries to green their products and reduce greenhouse gas (GHG) emissions and other environmental burdens [23]; therefore, the present study is the first of its kind in Pakistan which focuses on the LCA of marble production chain in Pakistan's Small Industrial Estate Mardan (SIEM) to calculate environmental impacts, water footprint, and energy demand of one-tonne marble tile production, from its extraction phase, to final store house or factory gate for investigation of emissions hotspots sources and to perform sensitivity analysis for identification of improvement opportunities in the entire marble production chain in Pakistan.

2. Material and Methods

2.1. Study Area

Mardan is the second-largest city in the Khyber Pakhtunkhwa (KP) province of Pakistan, with an estimated population of 2.34 million and an area of over 632 square kilometers (km^2). District Mardan is an industrial city with chemical manufacturing industries, paper industries, textile industries, pharmaceutical companies, cigarette industries, dairy farms and marble factories with chemical manufacturing industries, paper industries, textile industries, pharmaceutical companies, dairy farms marble factories, etc. Marble industries are situated in Small Industrial Estate, Mardan (SIEM). SIEM is located on Nowshera road, about 9.1 km from the main Mardan city at 34.12° N latitude and 72.02° E longitude, as shown in Figure 1. SIEM is divided into two zones or phases; it was established in 1974–1975 and consisted of 153 units, out of which 1 is closed and 152 are operational. In 152 units, the majority are marble factories, and a few are woodworks and plastic factories. The wastes of all industries in the study area are disposed of through small open drains into the main drain and finally go to the Rashakai canal. Marble is a vital building material and plays a vital role in a country's economy, but at the same time causes several environmental problems, such as waste being disposed of directly in freshwater and terrestrial ecosystems [7].

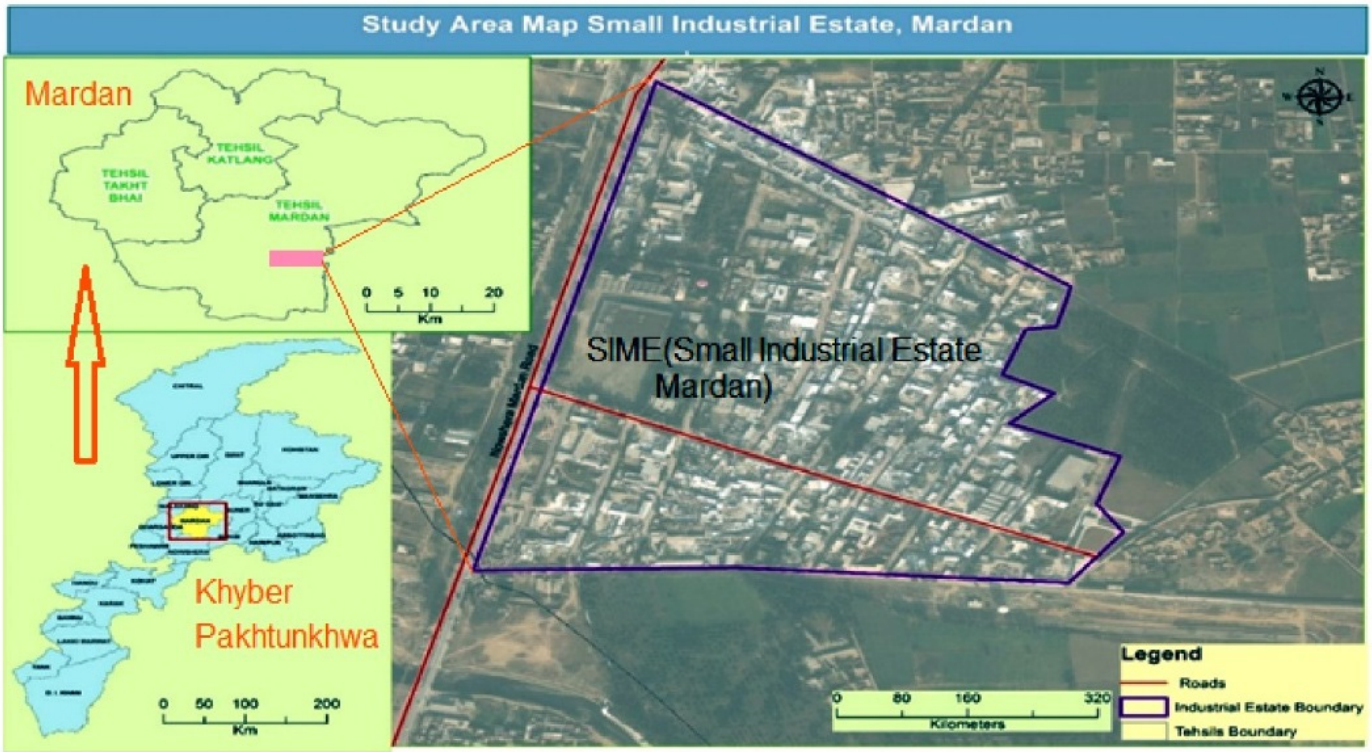

Figure 1. Study area location, Small Industrial Estate Mardan (SIEM), Pakistan.

2.2. Life Cycle Model and Inventory

2.2.1. Goal and Scope Definition

The goal of the present study was to assess the environmental sustainability of the marble tile production chain using the LCA methodology. The scope of the study consisted of marble stone quarrying, its transport to processing units, and marble tile manufacturing means finished marble tile production.

2.2.2. System Boundary of the Study and Functional Unit

The system boundary of the current study was limited to a cradle-to-gate analysis during the year 2017–2018, encompassing water scarcity index, environmental impacts, and cumulative energy demand from the extraction of stone, their transportation to processing units, and manufacturing of the final product and its transportation to storehouse or distribution centers, as can be seen in Figure 2. The functional unit for this study was one tonne of finished marble tile produced in the small industrial estate, Mardan city, KP, Pakistan. Water scarcity index (WSI) was calculated for one tonne of finished marble tile through different stages of the life-cycle of marble tile from extraction to finished product distribution to storehouse and marketing centers. All inputs and output data were expressed in terms of this reference unit.

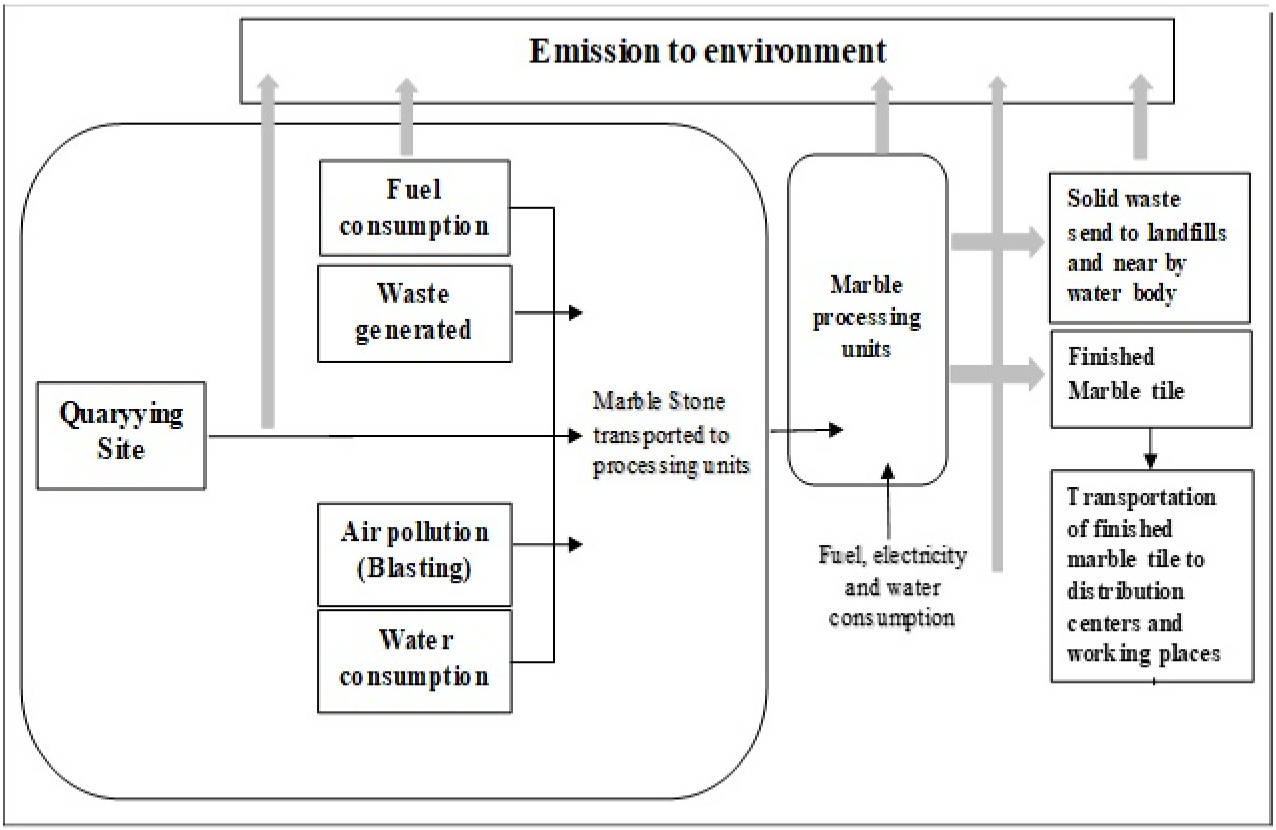

Figure 2. System boundary of marble production life cycle model, extraction to tile distribution centers.

2.2.3. Life Cycle Inventory (LCI):

The primary data were collected through questionnaire surveys and personal meetings at the extraction site and marble processing units at SIEM, Pakistan. Data regarding production capacity, fossil fuel consumption, water consumption, transportation activities, energy consumption, and solid waste generated were noted for the period 2017–2018. The inputs and outputs data regarding water, fossil fuels, and electricity consumption in raw block or stones quarrying, cutting and resizing, processing, and polishing of the finished marble tile were collected, as can be seen in Figure 3. The relevant data were collected from production managers and workers at quarrying sites and marble manufacturing units. The data were collected through questionnaire surveys from 43 different marble units at Small Industrial Estate, Mardan (SIEM) Pakistan, 10 extractions (quarrying) sites, and 10 construction sites. Secondary data were acquired from industry annual reports and peer-reviewed published literature/articles. The quantity of raw marble stone was obtained from marble processing units' managers and weighing stations. Similarly, the flow/discharge of installed water pumps was measured to estimate the cooling water used in the process; furthermore, electricity from the national grid was used for marble processing inside the units and therefore for energy estimation, monthly electricity consumption was obtained from each marble processing unit for energy estimation. The finished product was estimated by weighting the final polished tile and multiplying this value with the total number of tiles produced from the entire raw stone for the study period. In addition, the weight difference between the final product and raw stone gave the complete waste stone, marble slurry, and dust or powder produced during the tile production. Samples of polluted water were taken and tested in Laboratory for the amount of slurry.

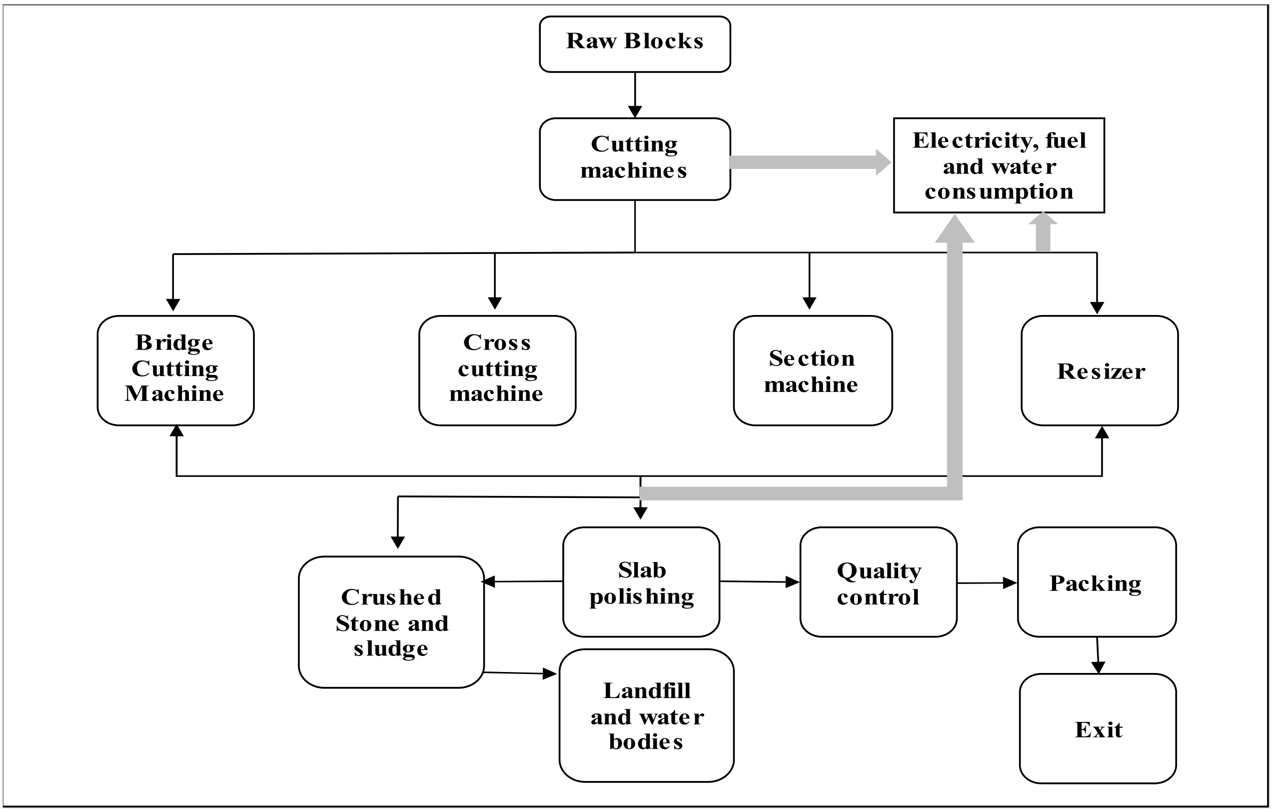

Figure 3. Flow sheet diagram of marble tile production chain in SIEM, Pakistan.

2.2.4. Estimation of Wastewater Discharge from Marble Processing Units

The amount of wastewater containing marble sludge generated was estimated by measuring the wastewater flow from marble units as industrial effluents using Equation (1) below.

$$\text{Wastewater flow rate (volume per day)} = \frac{W \times D \times L}{T} \quad (1)$$

W, *D*, and *L* are the width, depth, and length of the effluent pipeline or drain in meters, while *T* is the time in days (d). Wastewater discharge per unit tonne of the finished marble tile product was calculated by dividing the daily wastewater discharge by the daily marble tiles production. The amount of slurry generated from marble units was determined by standard methods 2540 [27].

2.2.5. Life Cycle Impacts Assessment (LCIA) and Modeling

Life cycle impact assessment included analyzing the impacts of one-tonne marble tile processing on different environmental compartments such as air, water, and soil. All the data from questionnaire surveys and Laboratory analysis were entered into Excel sheets for analysis. All the data were entered in SimaPro version 8.3 software developed by Pre-Sustainability Amersfoort City, Netherland for environmental impacts analysis, water scarcity index (WSI), CML 2000 v.2.05 methodology, and cumulative energy demand indicator present by default in SimaPro v.8.3 licensed by Dr. Majid Hussain, Department of Forestry and Wildlife Management University of Haripur, Pakistan was used for LCIA. Nine (09) environmental impact categories were zed by CML 2000 v.2.05 methodology as shown in Table 1, while four energy subcategories were assessed through the cumulative energy demand (CED) indicator. Similarly, the water scarcity index was calculated using [28] methodology. Environmental sustainability indicators (CED and WSI) are widely used for energy and water footprint assessment globally. CED shows all the sources of energy consumed to produce one tonne of marble tile production chain while WSI shows the water footprints of the one-tonne marble tile production chain. Environmental impact categories analyzed in this study are summarized in Table 1.

Table 1. Environmental impact categories and measurement units for each category were calculated in this study.

Impact Categories	Nomenclature	Units
Abiotic depletion	AD	kg Sb-eq
Acidification potential	AP	kg SO_2-eq
Eutrophication potential	EP	kg PO_4-eq
Global warming potential	GWP	kg CO_2-eq
Ozone layer depletion potential	OLD	kg CFC-11-eq
Human toxicity potential	HTP	kg 1,4-DB-eq
Freshwater aquatic ecotoxicity	FAE	kg 1,4-DB-eq
Terrestrial ecotoxicity potential	TEP	kg 1,4-DB-eq
Photochemical oxidation	PO	kg C_2H_4-eq

3. Results and Discussion

The water scarcity index (water footprint) was evaluated through LCA. The water footprint due to marble/stones extraction, processing, and finished marble tile production is shown in Figure 4. Overall, 3.63 m^3/t water scarcity or water footprint is caused by one-tonne finished marble tile production in SIEM, Pakistan. Different factors contributed to environmental footprints including electricity use during processing accounted for most of the impacts (48%), followed by paper packaging at the processing units (30%), plastic use at extraction sites and processing units (17%) and transport of stones/slabs to processing units (5%). Our results are following those reported in Ref. [29], which reported the water footprint for coke and coal as 1.03 m^3/t and 0.38 m^3/t, respectively, which is less than our study because the marble production chain is a more water-intensive process [6]. Similarly, [29] reported a total water footprint for the iron and steel industry as 6.7×10^8 m^3/t having a higher water footprint than the present study because the iron and steel production chain is more water-intensive than the marble tile production chain.

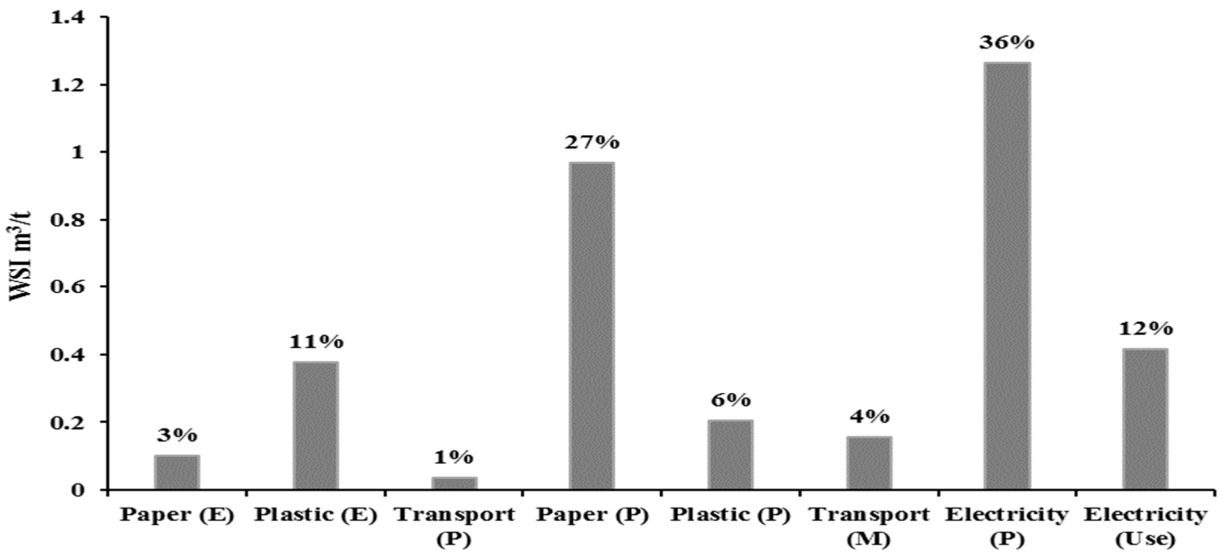

Figure 4. Cumulative water scarcity index for one-tonne marble tile production.

The contribution of different processes and input materials of one-tonne marble tile production to environmental impacts in Pakistan are summarized in Figure 5. The results revealed that the total GWP was 388 kg CO_2-eq for one tonne of marble tile production in Pakistan. Electricity use during the processing and polishing of marble tile is the primary source contributing (68%) to GWP, followed by transporting marble to processing units and the market (18%). Our results were following Ref. [13], in which a comprehensive LCA study on marble tiles in Turkey was conducted; their results also showed that the marble quarry (the unprocessed product before the marble plate) and electricity are the main contributors to the environmental effects of the marble plate. For marble quarries, the impact of diesel and electricity is significant. Abiotic depletion potential, global warming potential, and human toxicity potential were the main environmental loads of marble plate production [13]. In addition, in Ref. [14] the marble production system in Italy was studied, and it was reported that the highest burdens came from the marble quarrying operations due to the massive amount of fossil fuels and electricity consumption; furthermore, the marble production system emitted CO_2, SO_2, NOx, non-volatile organic compounds (NMVOC), and heavy metals [14,30,31]. Among the nine (09) environmental impacts caused by the marble production chain, [15] found the highest contribution of the marble tile production chain to GWP, AP, EP, and HT in Italy, which is in line with the results of the present study conducted in Pakistan. Carbon dioxide (CO_2) is the main greenhouse gas from different sources and inputs contributing to total GWP as shown in Figure 6. Our results are in accordance with Refs. [13–15], which analyzed the environmental impacts of the marble production chain using LCA; their results revealed that electricity and fossil fuels are responsible for the GWP impact category [21,32–34]. As there is no LCA of the marble production chain in Pakistan, we compared our results with other allied LCA-based studies; however, this is one of the limitations and weaknesses of the present study.

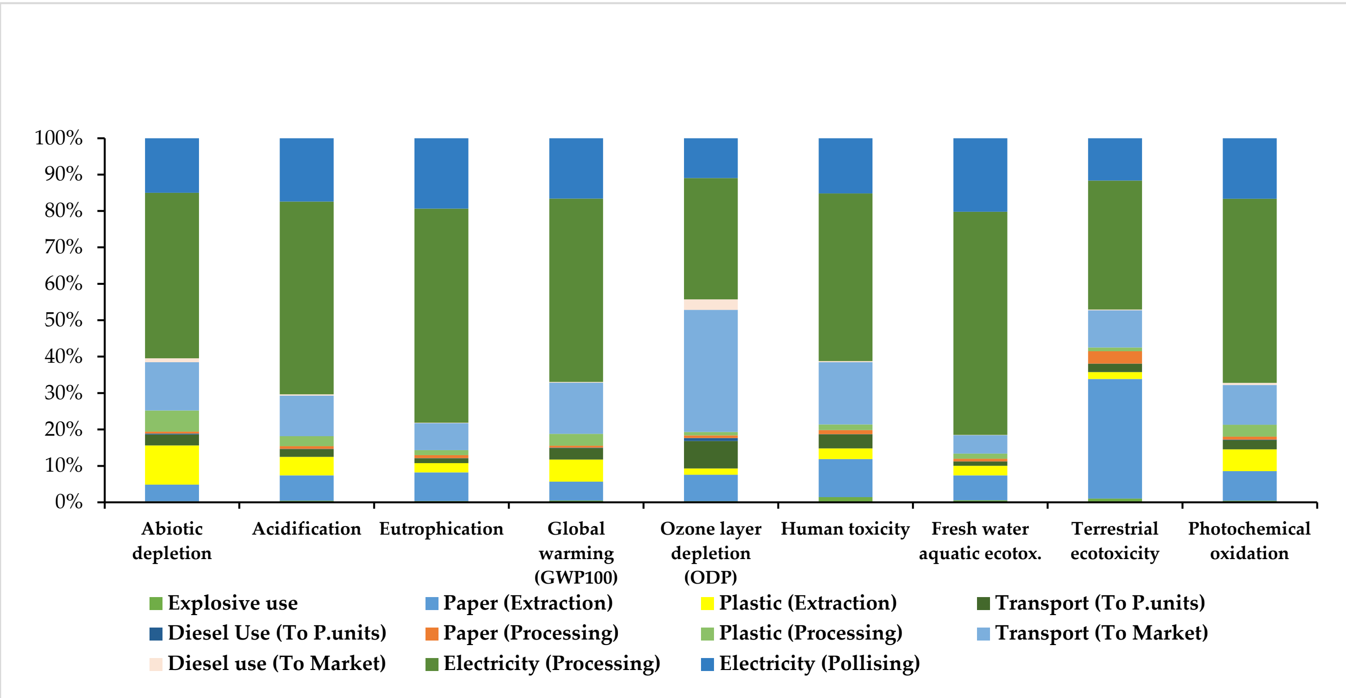

Figure 5. Percent (%) contribution of different inputs/processes to environmental impacts.

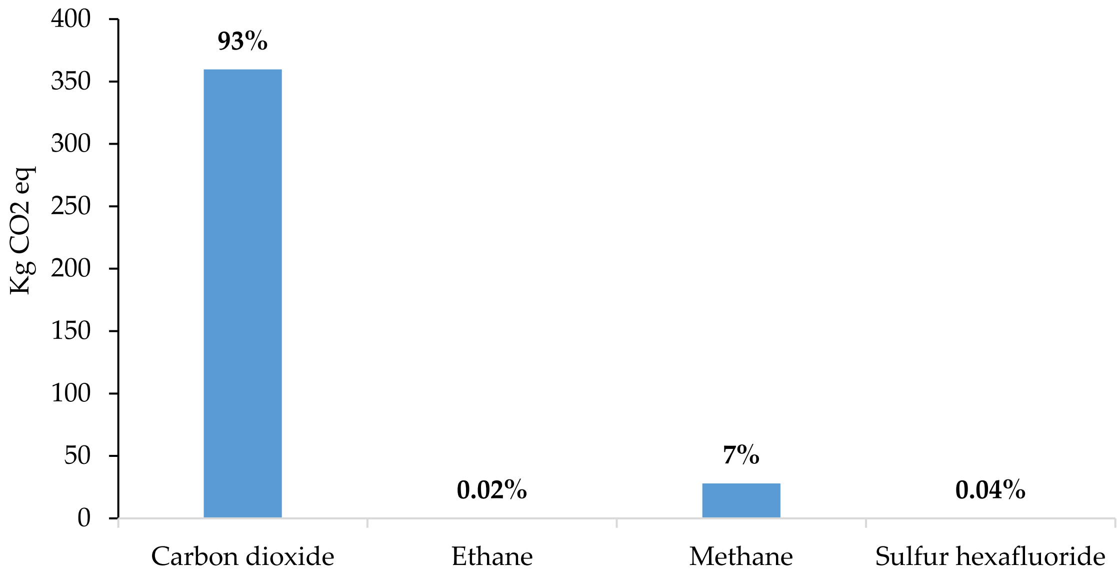

Figure 6. Various GHGs contributing to the GWP impact category.

On the other hand, AD is calculated as 7.1 × 10^{-5} kg Sb-eq Paper (75%), and electricity (17%) were responsible for most of the impacts in the AD impact category (Figure 7).

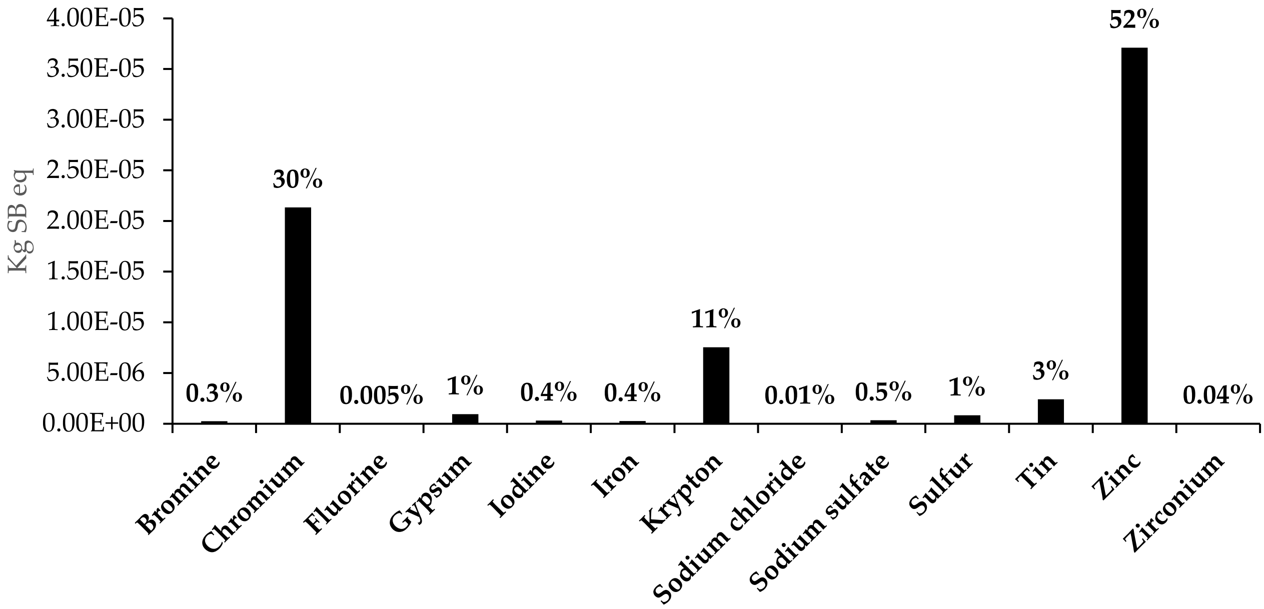

Figure 7. Major toxic pollutants contributing to AD impact category.

Hussain et al. (2017a) worked on environmental profile analysis of particleboard production. Urea-Formaldehyde (UF) resin production, natural gas, and transport are responsible for most of the impacts in AD category. Waismoradi et al. (2015) revealed the results of AD as 0.6 kg Sb-eq for one tonne of tangerine production, which is more than for marble tile production as they use agriculture machinery, which requires a huge amount of fossil energy. Similarly, 3.96 kg SO_2-eq of AP is caused by one tonne of marble tile from cradle to gate in Pakistan. For the AP impact category, electricity (56%) and paper (20%) were mainly responsible for most of the impacts, followed by explosives used at stones extraction sites (11%), transport (10%), and plastic use in the packaging (3%), which is similar to results in Refs. [13–15]; these results indicated that electricity consumption is the main contributor to SO_2 and NO_x emissions, which are responsible for the acidification of water bodies, as shown in Figure 8.

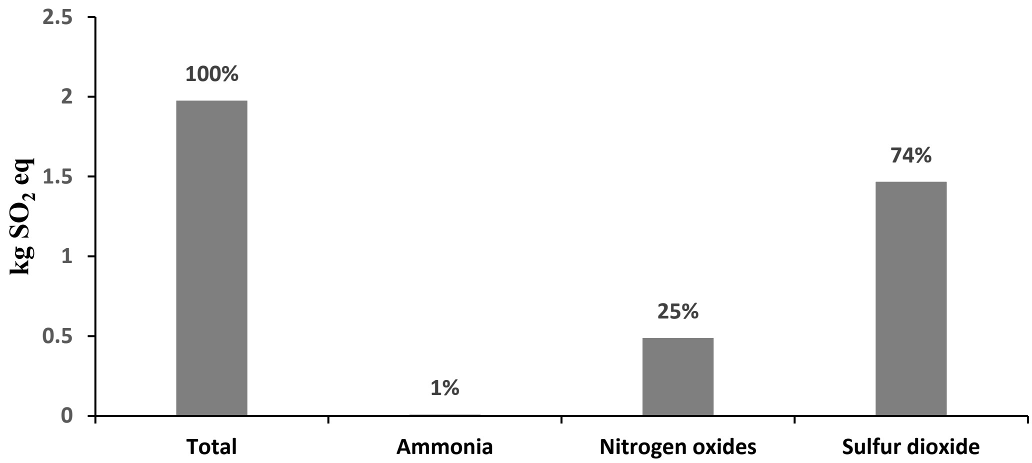

Figure 8. Percent (%) contribution of major contaminants to AP impact category.

One of the major sources of energy production in the marble tile manufacturing units is fossil fuel-based generators and machinery that release large quantities of emissions [14,15]. In comparison, for particleboard production, Iran's total AP was calculated as 1.82 kg SO_2-eq, and the responsible factors were UF resin (50.97%), electricity (30.86%), and transportation (11.79%) [35]. Similarly, for particleboard production [23], UF resin, transportation, and natural gas consumption are the main factor responsible for the AP impact category. Similarly, AP from tangerine production was reported as 2.95 kg SO_2-eq per tonne of tangerine production [36], which is less than marble tile production in Pakistan; moreover, in Ref. [37], an LCA of Nitrogen fertilizer use in winter wheat production systems was conducted; the results showed that for nitrogen fertilizer production, ammonia (58%), SO_2 (24%), and NO_x (18%) contributed to total AP per tonne of wheat grain produced. For the EP impact category, the results revealed 0.68 kg PO_4-eq, which is contributed by electricity (80%), paper (9%), transportation (8%), and plastic (3%) emitting NO_x, NH_3, and phosphorous as shown in Figures 9–11. Our results are in accordance with Refs. [13–15]; however, Waismoradi et al. (2015) calculated the value of 1.08 PO_4-eq; the value is higher than marble tile production because of the on-farm emission of ammonia and NO_X by the use of fertilizers and pesticides. Similarly, NH_3 and NO_x are the main contributors to the EP impact category [37].

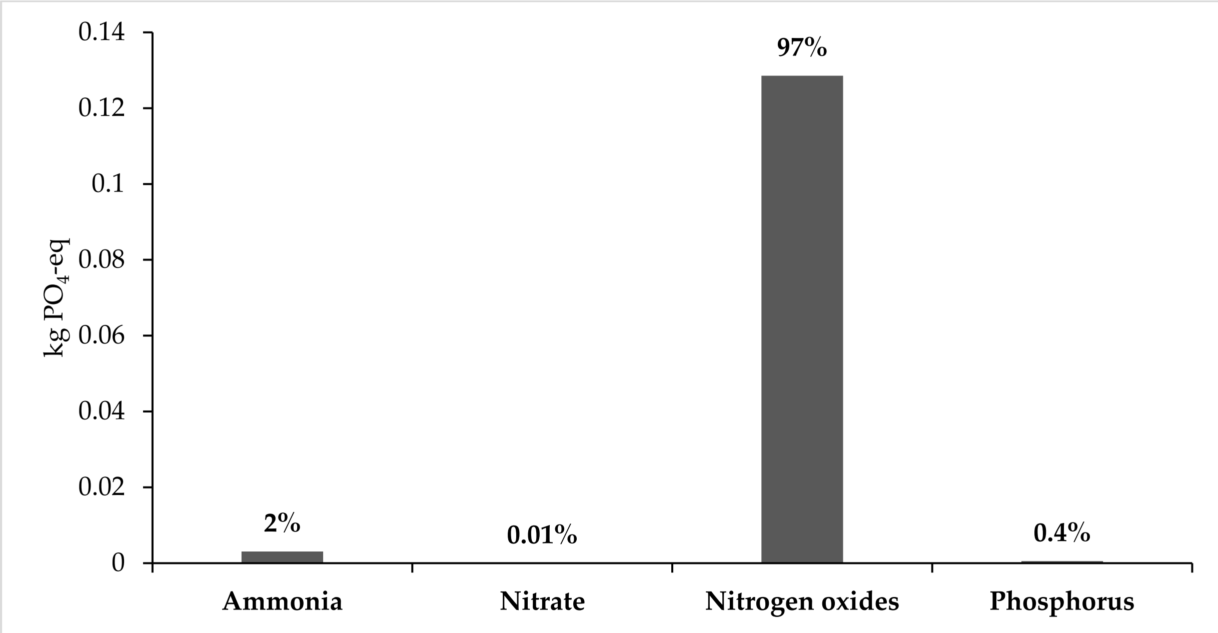

Figure 9. Percent (%) contribution of major contaminants to EP impact category in air matrix.

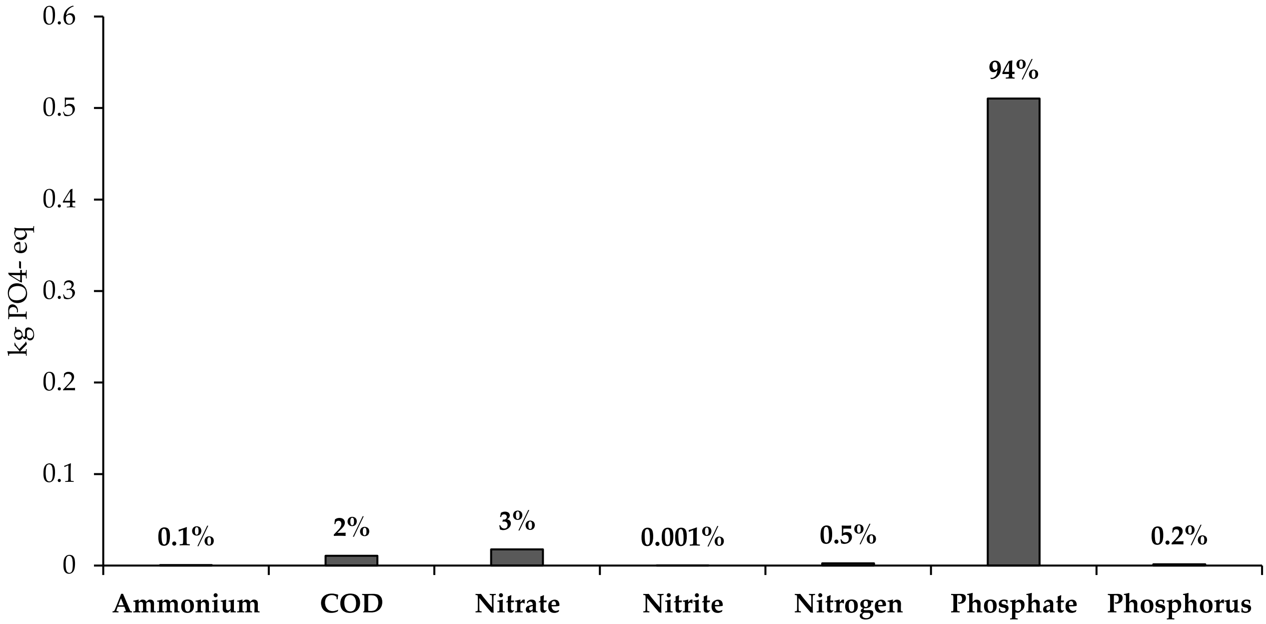

Figure 10. Percent (%) contribution of major contaminants to EP impact category in a water matrix.

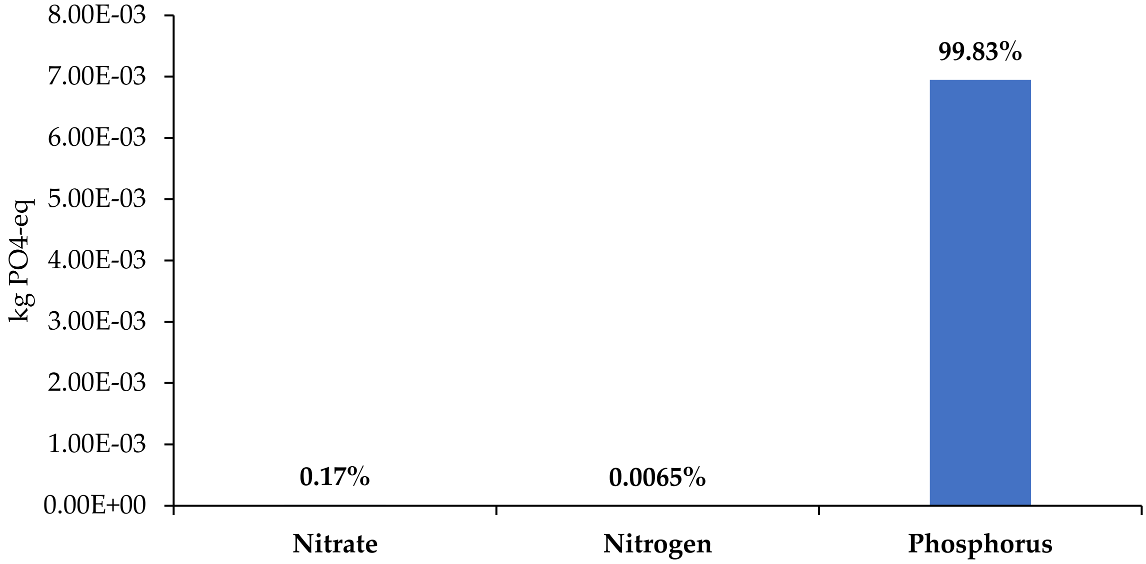

Figure 11. Percent (%) contribution of major contaminants to EP impact category in the soil matrix.

Different processes in marble tile processing units were accountable for most of the impacts in the OLD impact category, mainly electricity at processing units and polishing (88%), followed by paper and plastic wastes (10%) and transportation (2%). The results showed that 2.7×10^{-5} kg CFC-11-eq of OLD is caused by one tonne of marble tile from extraction to finished product having 83% contribution from methane emissions (Figure 12). Among the contributing factors, methane contributed the most (83%), whereas the least or minimum contribution comes from ethane (17%). Compared to the OLD potential of 0.0000052 kg CFC-11 eq. from tangerine production, [36] the OLD from marble tile was 5 times higher. Similarly, for the Iranian particleboard production chain, transportation was the main contributor (70%), followed by UF resin (20.68%) [7]. Machinery for transportation uses mainly diesel, which affects NO_x, SO_2, N_2O, and other emissions [7,13,15].

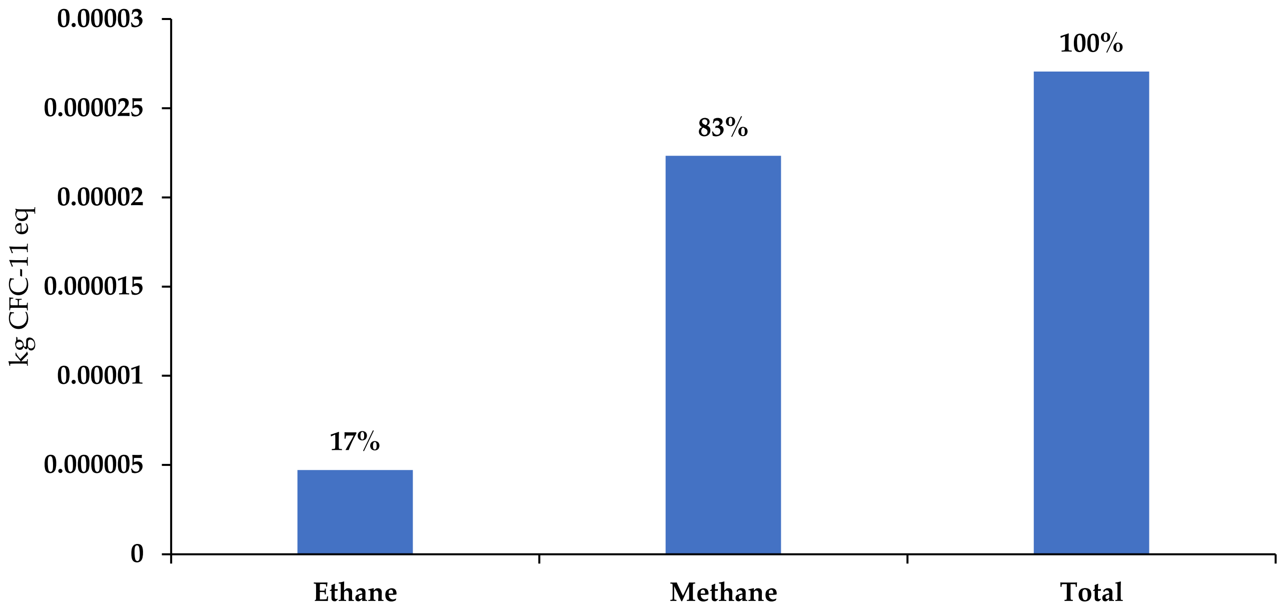

Figure 12. Percent (%) contribution of major contaminants to OLD impact category.

Human toxicity (HT) to different environmental compartments such as air, water and soil was assessed equitably to kg 1,4 dichlorobenzene (kg 1,4-DB-eq). To the atmosphere, 38.5 kg 1,4-DB-eq of human toxicity was caused by one tonne of marble tile from extraction to finished product. Transportation (95%), waste generated from marble units, and electricity used were different sources. The highest contribution from transport, wastes, and electricity were arsenic, antimony, nickel, benzene, copper, vanadium, and selenium [13–15], as shown in Figure 13.

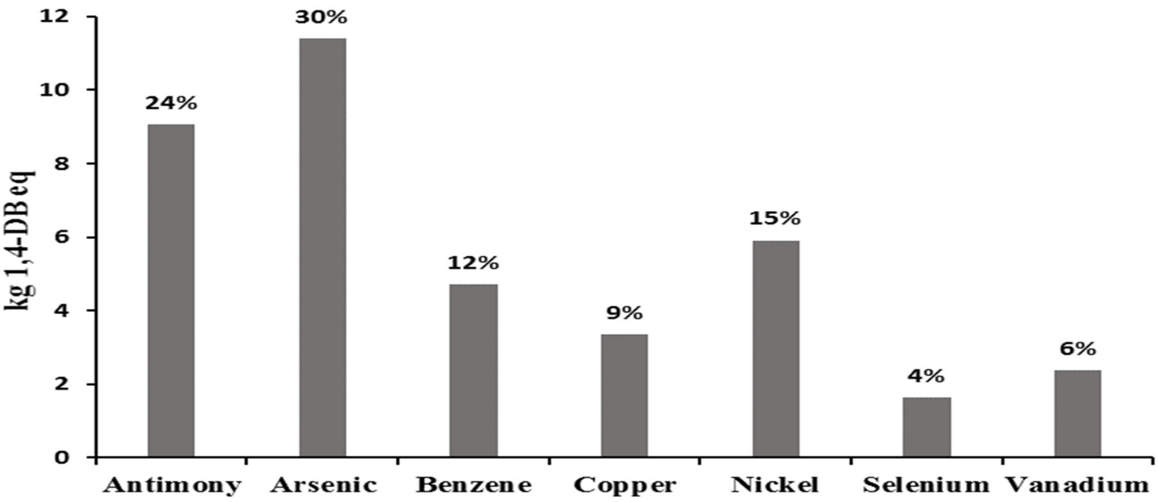

Figure 13. Percent (%) contribution of major contaminants to HT impact category in air matrix.

In the water matrix, 45.1 kg 1,4-DB eq HT is caused. Plastic waste (69%) and electricity (21%) are different sources that mainly contribute to the water compartment. Factors ng to these sources are mainly selenium, barium, nickel, and beryllium, as depicted in Figure 14. Soil compartment, per tonne of marble tile production from cradle to gate produced 0.77 kg 1,4-DB-eq HT impact category. Different sources that affect the soil compartment are electricity (51%) and paper and plastic wastes (49%). Factors that affect electricity and wastes contributing to human toxicity are chromium, vanadium, barium, arsenic, lead, and selenium [13–15], as shown in Figure 15. From the study of Tangerine, HT for one tonne of tangerine was 46 kg 1,4-DB eq [36] which is less than one tonne of marble tile production (84.33441 kg 1,4-DB eq) in Pakistan. Other studies on Iranian particleboard production show that UF resin, electricity, and transportation are the main sources of human toxicity for one tonne of particleboard production [35]. Pakistani particleboard production [23] shows that UF resin, transportation, and urea scavenger production were the primary contributing sources. The factors contributing to these sources are CO, CO_2, NO_x, VOC_s, and formaldehyde emissions from particleboard production.

Results for freshwater aquatic ecotoxicity (FAE) showed that 94.97 kg 1,4-DB-eq of FAE is caused by one tonne of marble tile from extraction to finished product. Electricity was the primary source contributing 86% to total FAE. Similarly, nickel, beryllium, cobalt, vanadium, copper, and zinc are the factors that contributed to the total FAE, as shown in Figure 16. From a previous study of tangerine, FAE values of 10.5 kg 1,4-DB-eq were noted for one tonne of tangerine [36], which is less than that for one tonne of marble tile production (94.97 kg 1,4-DB-eq) in Pakistan. Agriculture machinery had a crucial role in tangerine FAE. Also, electricity and UF resin were the sources responsible for the total FAE impact category [35]. Our results for the FAE impact category were similar to the findings of [13–15] for marble tile production systems.

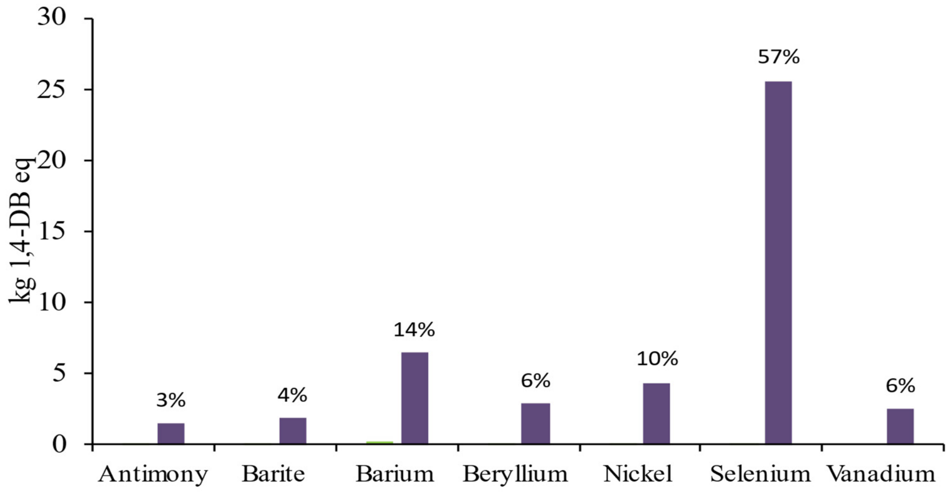

Figure 14. Percent (%) contribution of major contaminants to HT impact category in the water matrix.

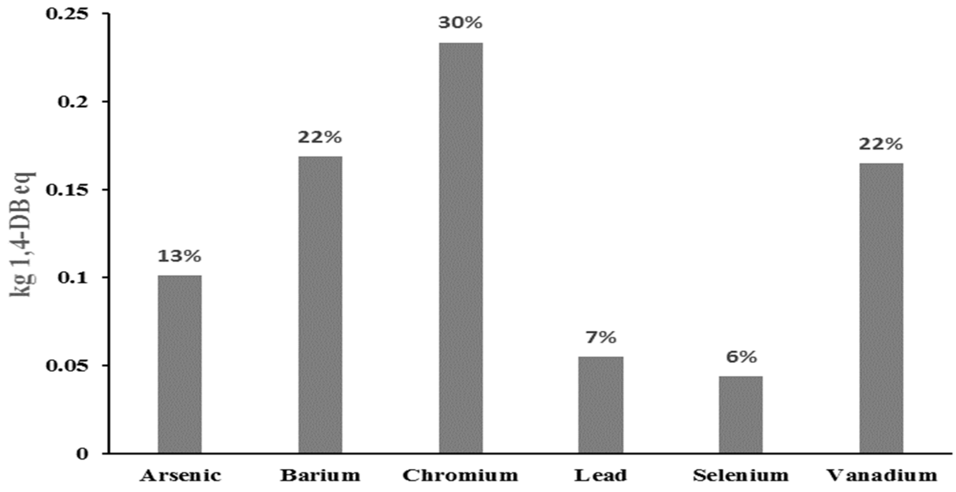

Figure 15. Percent (%) contribution of major contaminants to HT impact category in the soil matrix.

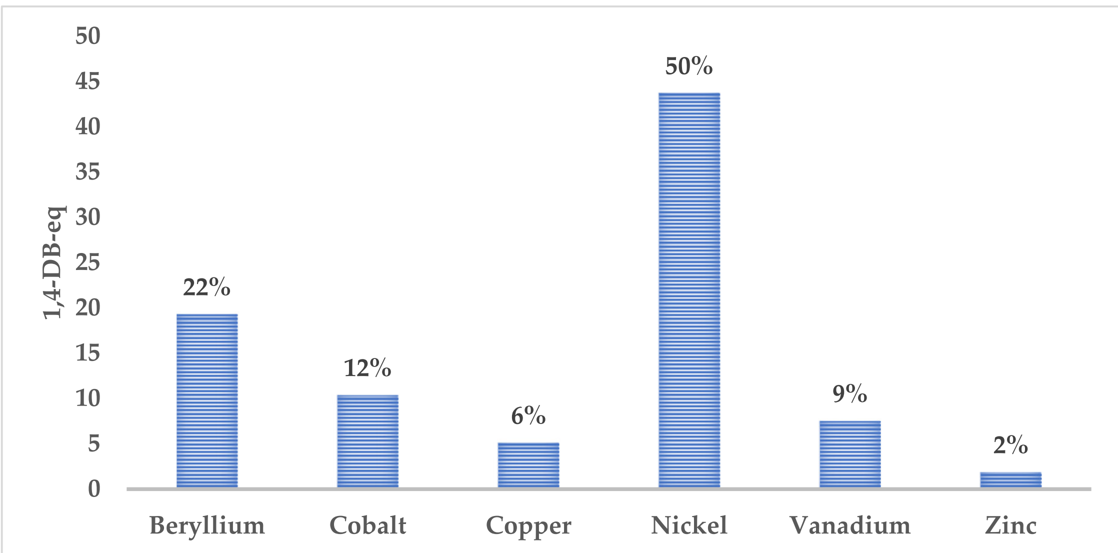

Figure 16. Percent (%) contribution of major contaminants to FAE impact category.

A total of 0.036788 kg 1,4-DB-eq of terrestrial ecotoxicity (TE) impact was caused to water. The results showed that 0.06493 kg 1,4-DB-eq of TE is caused by Soil. The total contribution to water is from mercury (100%). Electricity used, paper and plastic waste, and transportation cause TE with 45%, 42%, and 13% contribution. Factors that affect these sources are zinc, arsenic, vanadium, and barium, as shown in Figure 17.

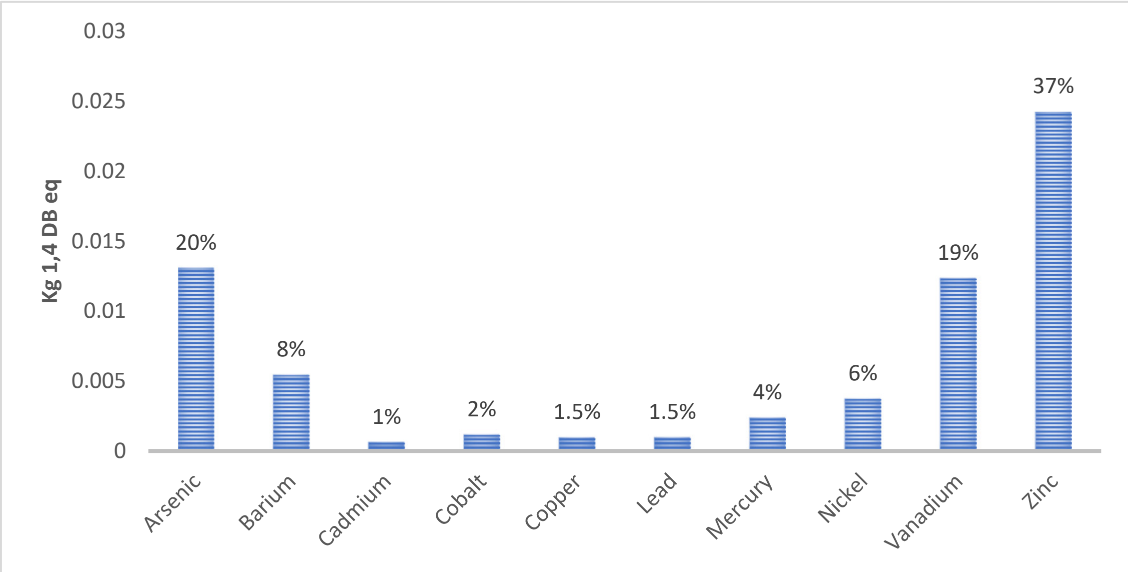

Figure 17. Percent (%) contribution of major contaminants to TE impact category in the water matrix.

In the air compartment, a total of 0.611371 kg 1,4-DB-eq TE is caused by one-tonne marble tile production in Pakistan. Again, electricity has the most contributing factor (65%), followed by transportation (17%) while paper and plastic wastes contributed (16%) and explosives used have the most negligible contribution of 2%. Mercury, vanadium, arsenic, nickel, copper, lead, and zinc affect these sources, as shown in Figure 18.

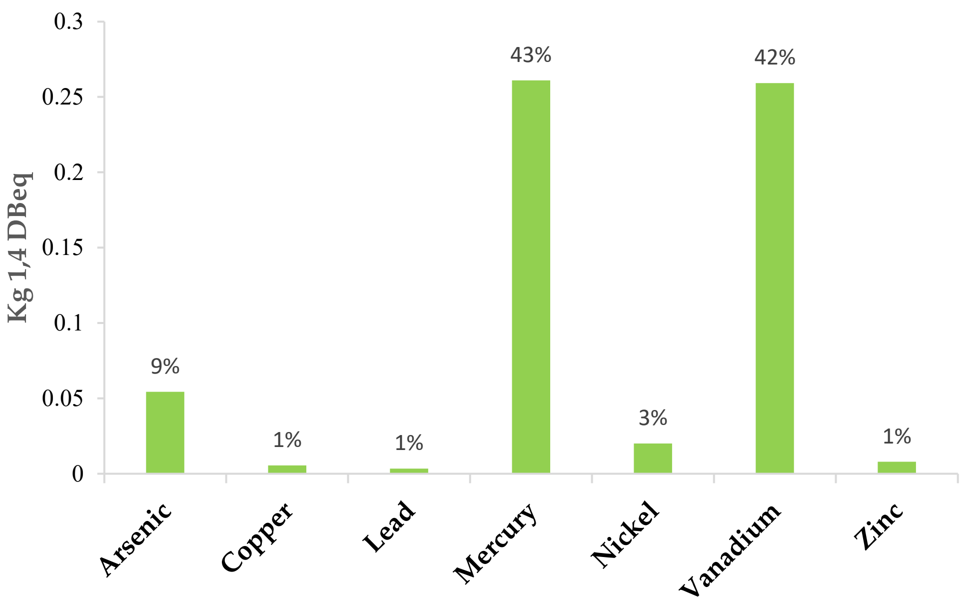

Figure 18. Percent (%) contribution of major contaminants to TE impact category in air matrix.

The previous study of one-tonne tangerine production TE is 0.15 kg 1,4-DB-eq [20], which is less than one tonne of finished marble tile production (0.71 kg 1,4-DB eq) because of fewer emissions. Photochemical oxidation (PO) showed that 0.065684 kg C_2H_4-eq of PO is caused by one tonne of marble tile from extraction to finished product. For PO transportation, plastic and paper wastes and electricity are the sources. SO_2, pentane, butane, propane and hexane are the major factors contributing to these sources shown in Figure 19. PO is also mainly due to transportation [23]. From the study of tangerine, PO was 0.04 kg C_2H_4 eq [36] which is less than one tonne of marble tile production (0.06 kg C2H4 eq) in Pakistan. The main hotspots have been demonstrated in Table 2, where significant contributors to most of the environmental impact categories were identified. Electricity was the most critical hotspot as it contributes to almost all 10 environmental impact categories. Transportation was identified as a hotspot in AD, EP, GWP, HT, and PO impact categories; moreover, paper packaging wastes are hotspots in AD, AP, EP, TE, and PO impact categories. The same is for explosives in AD impact and plastic packaging wastes in the PO impact category.

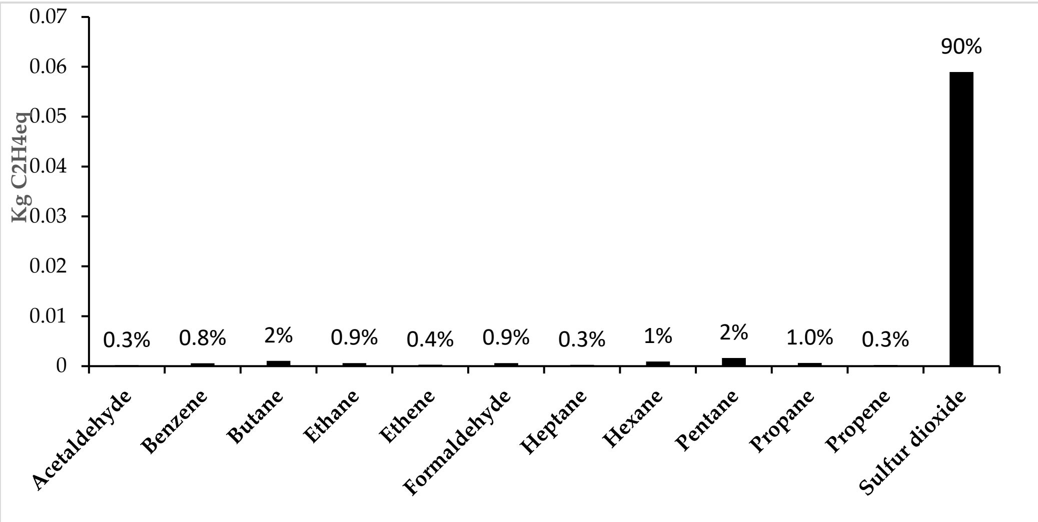

Figure 19. Percent (%) contribution of major contaminants to PO impact category.

Table 2. Environmental Life cycle impact indicators and their hotspots in the marble production chain.

Impact Category	Unit	Total	Hotspots Sources
Abiotic depletion	kg Sb eq	7.12×10^{-5}	Paper wastes, electricity
Acidification	kg SO_2 eq	3.96	Paper wastes, electricity, explosives, transportation
Eutrophication	kg PO_4 eq	0.68	Electricity, Paper wastes, transportation
Global warming (GWP100)	kg CO_2 eq	387.81	Electricity, transportation
Ozone layer depletion (OLD)	kg CFC-11 eq	2.7×10^5	Electricity, transportation
Human toxicity	kg 1,4-DB eq	84.34	Transportation, electricity, plastic wastes
Fresh water aquatic ecotoxicity	kg 1,4-DB eq	94.97	Electricity, transportation, paper wastes
Terrestrial ecotoxicity	kg 1,4-DB eq	0.71	Electricity, paper wastes
Photochemical oxidation	kg C_2H_4 eq	0.065	Transportation, paper and plastic wastes, electricity

A total of 5863.411 MJ energy was consumed by one tonne of finished marble tile from the extraction phase to the finished product in SIEM, Pakistan. Different energy sources contributing to the total energy consumed were mainly renewable fossil fuels (95%), while the most negligible contribution comes from renewable water (5%) in the one-tonne marble tile production chain in Pakistan. The contributing sources were electricity at processing units contributed more energy consumption (41%), followed by transport to market (16%), electricity used during the polishing of marble tile (14%), and paper wastes at the extraction site (12%). In contrast, the lowest contributing sources were plastic wastes at processing units (7%), followed by paper wastes at extraction sites (5%), transport to processing units (4%), and diesel use to market (1%). As can be seen in Figures 20 and 21, among various processes, electricity, and transportation are the two most energy-intensive processes following other LCA-based studies [23,35].

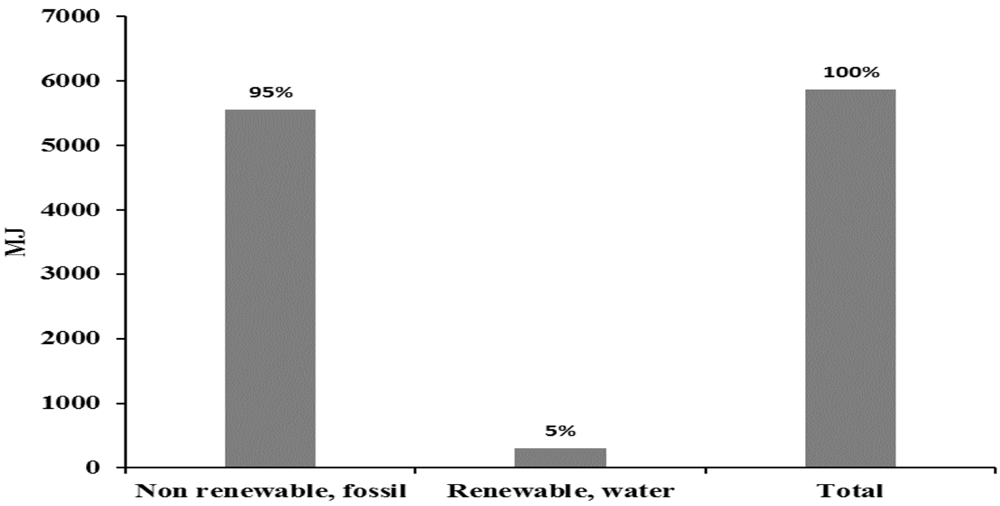

Figure 20. Various energy sources contributing to CED for one tonne marble tile production chain.

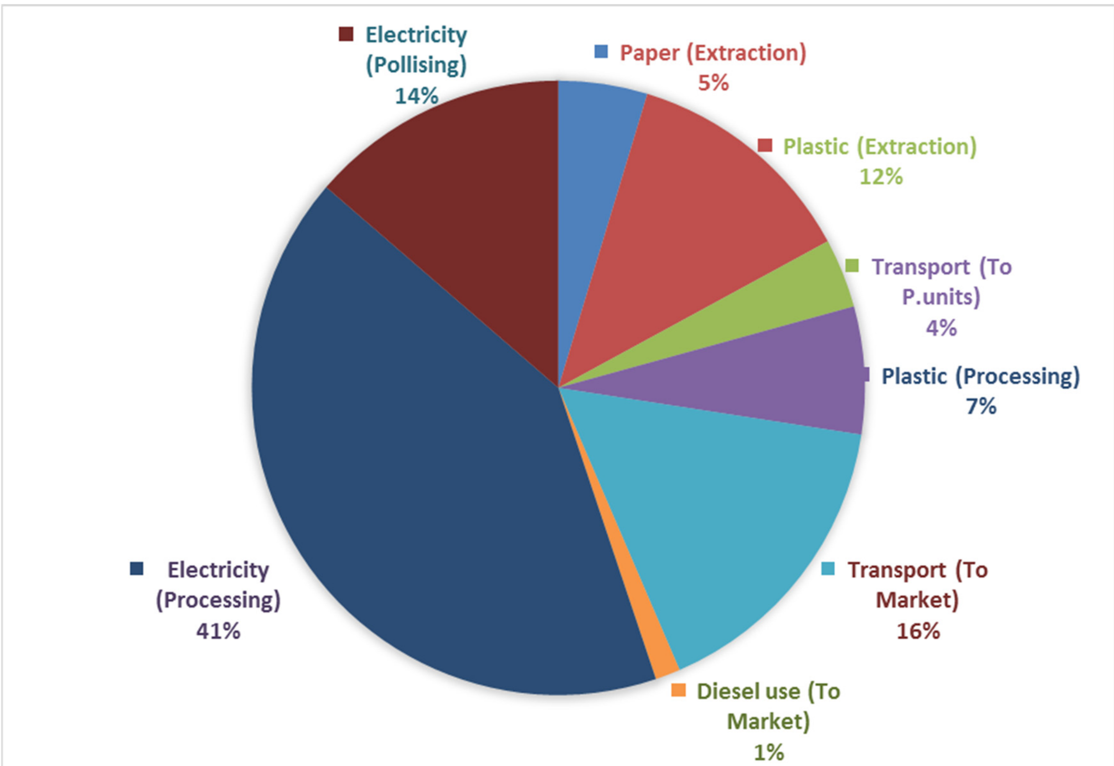

Figure 21. Various processes/inputs contributing to CED for one-tonne marble tile production chain.

Wastewater flow rate and slurry were determined for ten different marble manufacturing units at SIEM, Pakistan, as summarized in Table 3. The average wastewater discharge in SIEM was 318 ± 34 m^3/day, whereas the average wastewater per tonne of marble tile produced was 3.1 ± 1.7 m^3/d/t. The average slurry produced was 49 ± 5 g/L, with the highest contribution from Two-Star Marble Factory (58.02 g/L) and Al-Noor Marble Factory (54.34 g/L), SIEM, Pakistan. From the comparison, it is clear that the marble unit with more wastewater and slurry production had more machinery for marble processing and overall more production volume of marble tiles, as shown in Table 3.

Table 3. Wastewater flow rate and total solid substances (amount of slurry) of various marble units in SIEM.

S. No	Unit Name	Production/Month	Waste Flow Rate (m^3/d)	Amount of Slurry (g/L)
1.	Fazal Marble Factory	46.8	283.04	42.44
2.	New Kashmir Marble Factory	114.4	319.68	45.44
3.	Al-Noor Marble Factory	187.2	276.48	54.34
4.	New Punjab Marble Factory	130	354.24	50.68
5.	Shams Marble Factory	58.5	371.52	44.34
6.	Galaxy Marble Factory	124.8	336.96	48.04
7.	Two-Star Marble Factory	195	276.48	58.02
8.	Haksar Marble Factory	124.8	339.96	47.62
9.	Sheraz Marble Factory	130	328.32	49.32
10.	New Sohail Marble Factory	130	288.48	51.82

4. Conclusions and Recommendations

The present study was conducted on an environmental sustainability assessment of Pakistan's marble tile production chain from a life cycle perspective. The water footprint at the extraction site was calculated as 0.533148 m^3/t, at processing units, WF was 2.601784 m^3, and at construction or during use, it was 0.416269 m^3/t, respectively. The total water footprint of one tonne of finished marble tile from cradle to gate was 3.627151 m^3/t. Nine (09) environmental impacts were analyzed in this study. Global Warming Potential (GWP) contributed 387.818761 kg CO_2-eq (62%) to all impact categories for one tonne of finished marble tile production. Abiotic Depletion (AD) was the second-largest impact category analyzed, contributing 7.12865E-05 kg Sb-eq (0.5%) to total environmental impacts. Acidification (AP), the third-largest impact analyzed, gives a total of 3.964385 kg SO2-eq (0.3%) for one tonne of marble tile production. Cumulative Energy Demand (CED) was calculated at 5863.411 MJ. Various sources contributing were non-renewable fossils (95%) and renewable water (5%). The results of this study showed that reducing electricity (by use of the latest and automatic machinery) and waste materials, especially paper and plastics, can reduce environmental impacts. Small industrial estate Mardan did not have any wastewater recycling plants. Wastewater directly flows to nearby water bodies and land; this wastewater should be treated before discharge. Environmental impact improvements must be attained by using new and latest automatic machinery, reducing waste material, reducing the distance between quarrying sites and processing marble tile units, and installing wastewater treatment and recycling plants.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

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