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Impact of Crushed Natural Aggregate on Environmental Footprint of the Construction Industry: Enhancing Sustainability in Aggregate Production

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Abstract: This research addresses a critical gap in understanding the environmental impact of natural rock aggregate production in Sri Lanka. The study employs life cycle assessment (LCA) and SimaPro Software to simulate natural coarse aggregates' extraction and manufacture process. Key findings reveal significant environmental impacts, with human carcinogenic toxicity (2.45938×10^{-6} Pt), eutrophication of freshwater (1.59326×10^{-6} Pt), and fossil resource scarcity (1.4823×10^{-6} Pt) being significant concerns. The crushing process in particular shows the highest levels, contributing 2.21×10^6 to human carcinogenic toxicity and 8.92×10^7 to freshwater eutrophication. High electricity consumption, particularly from hard coal in electricity generation, is identified as a primary contributor. Although the sole source of coarse aggregate production in Sri Lanka is natural rock crushing, there is a lack of country-specific environmental impact assessment data for this process. This study provides a valuable dataset for the Sri Lankan construction industry, covering various environmental impact categories and encompassing the sub-processes inherent to natural rock aggregate production. The research highlights the necessity of implementing sustainable practices in quarry operations, proposing a transition towards more environmentally friendly energy sources. By quantifying environmental effects, this study provides valuable insights for stakeholders in the construction sector, enabling informed decision-making and targeted interventions to enhance overall sustainability while offering aggregate manufacturers opportunities to adopt more sustainable practices.

Keywords: aggregate production; crushed natural aggregate; environmental impact; life cycle assessment; sustainable construction



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1. Introduction

Natural aggregates, such as crushed stones and sand, are essential mineral raw materials extracted from the earth. These materials are produced by crushing bedrock or processing naturally occurring unconsolidated gravel and sand [1,2]. Playing a crucial role in construction, mineral-based aggregates account for approximately 7% of global energy consumption due to extraction, processing, handling, and utilisation [3]. According to [4], the estimated worldwide aggregate consumption per year is 50 billion tonnes. Globally, almost 40% of raw stone, gravel, and sand are voraciously consumed by the ever-expanding building sector, highlighting its substantial demand within this industry [5,6]. Aggregate extraction for the global construction requirement is projected to increase from 24 to 55 million tons annually between 2011 and 2060 [7].

Accordingly, extensive global aggregate use, including mining, processing, and transporting substantial aggregate quantities, significantly impacts the Earth's habitat [8,9]. The

construction sector's reliance on primary aggregates is unsustainable due to their non-renewable nature [4]. Although aggregates are the most extensively consumed material globally, with demand consistently growing [10], knowledge about their environmental footprint throughout their life cycle remains limited and uncertain [11]. Furthermore, Identifying environmentally sustainable sources of aggregates is crucial for industrial decision-makers [9]. In Sri Lanka, where crushed stone is a conventional and widely used coarse aggregate, there has been no assessment of the environmental impacts of quarry mining for rock aggregates despite its importance in informed decision-making.

To address these concerns and enhance sustainability, the construction industry is increasingly adopting measures such as life cycle assessment (LCA) to manage resource use and emissions more effectively [2]. LCA is specifically used to quantify and assess the environmental impacts of aggregate extraction and production processes [12]. Quantifying the environmental consequences of building materials is often challenging due to variations in project locations, the sources of LCA databases, and a lack of transparency [13]. Ref. [14] (2018) emphasise the pressing need for a national database to quantify and assess the environmental impact of building materials. Although the life cycle approach to environmental impact in building construction is extensively debated globally, it remains relatively unknown in Sri Lanka due to the absence of country-specific data sets and the cost and complexity challenges in conducting these assessments [15]. A national database would enhance the precision of environmental impact evaluations for buildings in Sri Lanka.

This study aims to assess and evaluate the environmental impacts of coarse aggregate production, with a specific emphasis on crushed natural stone in Sri Lanka. By developing a comprehensive national dataset and identifying key environmental hotspots, this research not only highlights critical areas for future improvement but also provides essential data to inform policy-making. The unique methodology introduced in this study is specifically tailored to Sri Lanka, where no similar comprehensive assessments have previously been conducted. The development of this dataset and the focus on identifying environmental hotspots provide new insights on decision making on use of natural coarse aggregate and pioneering approach to search for alternative aggregate production approaches to improve the use of more sustainable material in the country's construction industry.

1.1. Environmental Impacts Associated with the Aggregate Quarries

Concrete is the most widely used human-made material globally [16]. Consequently, there is an increased need for raw construction materials [17]. Coarse aggregates typically comprise between 30% to 60% of raw virgin material in its composition, adjusted based on the desired compressive strength, modulus of elasticity, and other required properties [18,19]. The mining of aggregate inevitably results in some environmental impacts, which cannot be disregarded [20]. Natural aggregates are not readily available and have notable negative environmental impacts during production [21,22]. Coarse aggregate production includes several phases, such as drilling, blasting, digging, crushing, screening, stockpiling, and transportation, with aggregate typically produced by crushing bedrock or large boulders [23]. Each of these phases include increased energy usage and the resulting release of greenhouse gases, degradation and instability of landscapes, contamination of water resources, and air pollution caused by particulate matter [21,24]. Certain environmental impacts from aggregate mining are engineering-related and are typical of most construction projects [20]. Nonetheless, aggregate extraction and processing lead to environmental impacts such as alterations to the landscape, noise, dust, vibrations from blasting, and deterioration of groundwater and surface water [1].

Coarse aggregate significantly impacts terrestrial acidification and eutrophication during concrete production [25]. Furthermore, gathering natural aggregate through surface mining leads to soil erosion and the degradation of ecosystems [25]. Producing 1 ton of natural coarse aggregate from crushed stone incurs an environmental load of 11.5 m Pt in net eco-points (which stands for impact per person-time) alongside an associated energy consumption range of 496–518 MJ and greenhouse gas emissions ranging from 32–33 kg

CO₂e in Hong Kong [3]. The energy-intensive crushing process notably influences CO₂e emissions in Brazil's coarse aggregate production [26].

Recycled aggregate is anticipated to reduce raw material scarcity in the construction industry by repurposing waste concrete into usable resources [22]. As per research conducted by [27], recycled aggregates have a low environmental impact compared to natural aggregates [2] further highlighting that recycled aggregates are particularly beneficial in reducing impacts such as aquatic acidification, aquatic ecotoxicity, ionising radiation, and global warming. The elevated impact values associated with natural aggregates arise from the intensive and disruptive methods used to extract them from the ground. Accordingly, substituting natural aggregate with recycled aggregate will be a better solution for the high environmental impacts. Conversely, Ref. [23] highlighted that the environmental footprint associated with utilising recycled aggregate was discovered to be double compared to that of using natural aggregate. This discrepancy is primarily attributed to the more straightforward production process of natural aggregate, which consumes less energy when compared with the energy consumption associated with recycled aggregate [28]. Hence, a comprehensive investigation to determine the most sustainable choice between utilising natural resources and recycling remains to be conducted.

1.2. Production Trends and Environmental Challenges in Sri Lankan Coarse Aggregate Sector

Sri Lanka possesses a wealth of essential natural resources vital for diverse industries. With the country's growing urban expansion, the construction sector's continual need for rock quarrying is escalating rapidly as a primary raw material in the construction industry [29]. Quarries and crushers are essential requisites for the construction industry in Sri Lanka [30]. In Sri Lanka, nearly all coarse aggregate has been sourced from crushed rock, so the demand for an alternative has not emerged [31]. Consequently, rock aggregate quarries operating in Sri Lanka have resulted in several social and environmental issues [29]. There are more than 2500 industrial mining license (IML)-grade quarries in Sri Lanka, with production ranging from 1500 m³ to 15,000 m³ per month [32]. The functioning of this extensive number of natural aggregate extraction and production quarries contributes significantly to enormous negative environmental impacts.

The demand for coarse aggregate in the Sri Lankan construction sector is met through local suppliers. The Geological Survey and Mines Bureau (GSMB) is the government body that oversees and governs the exploration, extraction, processing, logistics, storage, and local and international trade facilitation of minerals by issuing licenses in Sri Lanka. The GSMB monitor the protective measures taken by the quarry owners in terms of workers and environment, such as dust control, vibration, and sound level at the blasting of rock. However, it is essential to note that the authority of GSMB to grant licenses is restricted and must adhere to the limitations and terms outlined in the Mines And Minerals Act (No. 33 of 1992). Moreover, the Central Environmental Authority (CEA) plays a vital role by reviewing and monitoring the environmental impacts of natural aggregate quarry operations. Figure 1 shows the annual aggregate production (gravel, sand and rock aggregate) in Sri Lanka over nine years (2015–2023) as reported by the GSMB data.

According to the Figure 1, in 2018, the overall aggregate consumption (sand, gravel, and rock aggregate) reached its highest point at 0.09 billion tonnes. However, it decreased to 0.05 billion tonnes in 2019 and 2020 as a result of the economic consequences of the COVID-19 epidemic. The overall pattern is reflected in the utilisation of rock aggregate, which reached its highest point in 2021 at 0.037 billion tonnes after seeing a consistent rise from 2015 to 2018. The decrease in the use of rock aggregate to 0.020 billion tonnes by 2023 corresponds with the general decrease in the overall consumption of minerals, suggesting that the obstacles impacting the construction sector were substantial. Both the overall and rock aggregate consumption experienced a significant decline during the epidemic, followed by a gradual rebound as economic conditions stabilised.

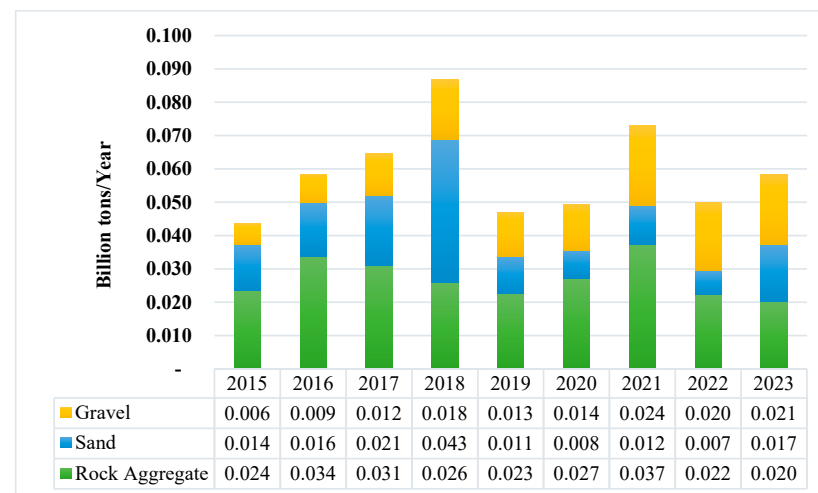


Figure 1. Rock aggregate, sand, and gravel production in Sri Lanka in billions of tons per year. Source: Prepared by authors based on the data provided by GSMB.

According to Figure 2, Sri Lanka's annual average aggregate production of 0.06 billion tonnes is much more modest than that of the other countries and areas mentioned. Sri Lanka's production output, a mere 0.4% of China's substantial 15 billion tonnes, demonstrates its insignificant contribution to global production. When compared, Sri Lanka's production is significantly smaller than that of other major producers, like India (1.2% of its 5 billion tonnes) and South Africa (1.82% of its 3.3 billion tonnes). Sri Lanka's contribution to production is considerably smaller than that of regions like South America and Australia/New Zealand, even among the smaller producers. Sri Lanka's insignificant production size accounts for about 0.15% of the total global output of 40.56 billion tonnes. The low production level can be attributed to various factors, such as the scarcity of natural resources, a smaller industrial foundation, and potentially lower levels of technological advancement. In addition, Sri Lanka's smaller population and shorter demand level than other countries also contribute to its lower production figures.

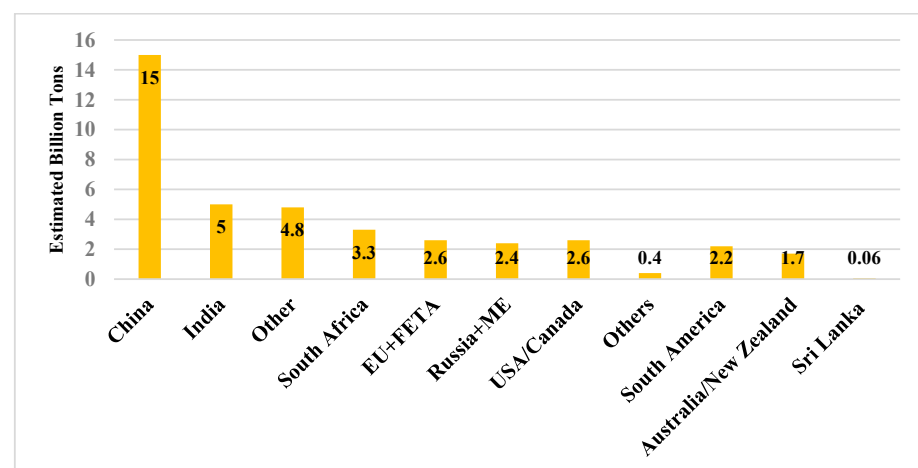


Figure 2. Global estimated annual aggregate production (in billions of tons) by country and region, including Sri Lanka. Source: Prepared by the authors based on data from the [33] and average production statistics for Sri Lanka calculated from available data from the GSMB.

2. Method

The LCA is a widely accepted method for quantifying environmental impacts. LCA quantifies the environmental impacts from the production process of course aggregate, including mineral extraction and processing of natural aggregates.

2.1. LCA Methodology

The critical phases in conducting an LCA study encompass goal and scope definition, performing LCI (life cycle inventory) analysis, conducting life cycle impact assessment (LCIA), and interpreting the results [34]. The scope of the LCA outlines the functional unit, system boundaries, LCIA methodology, impact categories, assumptions, and restrictions [35]. LCI involves gathering input and output data of the unit processes and employing calculation methods to accurately measure the pertinent inputs and outputs [14]. The LCIA assesses the potential environmental consequences using chosen environmental impact categories and associated characterisation models. Furthermore, this phase assigns the LCI results to these predetermined impact categories [35].

2.1.1. Goal and Scope of the Research Study

The definition of goal and scope stipulates the objective and scope of the LCA study [35]. This research study aims to quantify and assess the environmental impact of natural rock aggregate extraction and production process, including crushing. Furthermore, natural aggregates are obtained from solid rock formations of diverse origins, encompassing igneous, sedimentary, and metamorphic [36]. This research study focused on a sedimentary rock.

This research study employs a declared unit, deviating from a functional unit, as the scope of this study does not encompass the entire product life cycle but the cradle-to-gate scope. ISO 21930 for sustainability in buildings and civil engineering works core rules for environmental product declarations of construction products and services defines the term “declared unit” as the unit when an LCA study cannot outline the reference scenario for the entire life cycle of construction works [37]. Consequently, in this study, the declared unit is the extraction and crushing (production) of 1 kg of coarse aggregate.

Figure 3 illustrates the system boundary of the aggregate production process through the cradle-to-gate approach. Accordingly, the process is initiated with land clearance and the preparation of boreholes for subsequent blasting. Post-blasting, the fractured rock is transported to the crusher. Then, the extracted material undergoes crushing, passes across a screening device, and is sorted according to size using a sieve. Natural aggregate production involves raw materials, energy (electricity and fuel), water consumption, and air emissions. After establishing the declared unit, inputs and outputs for each related process are converted to a per-1 kg value, determined by the total actual production of the selected quarry (quantity in kg) for one year.

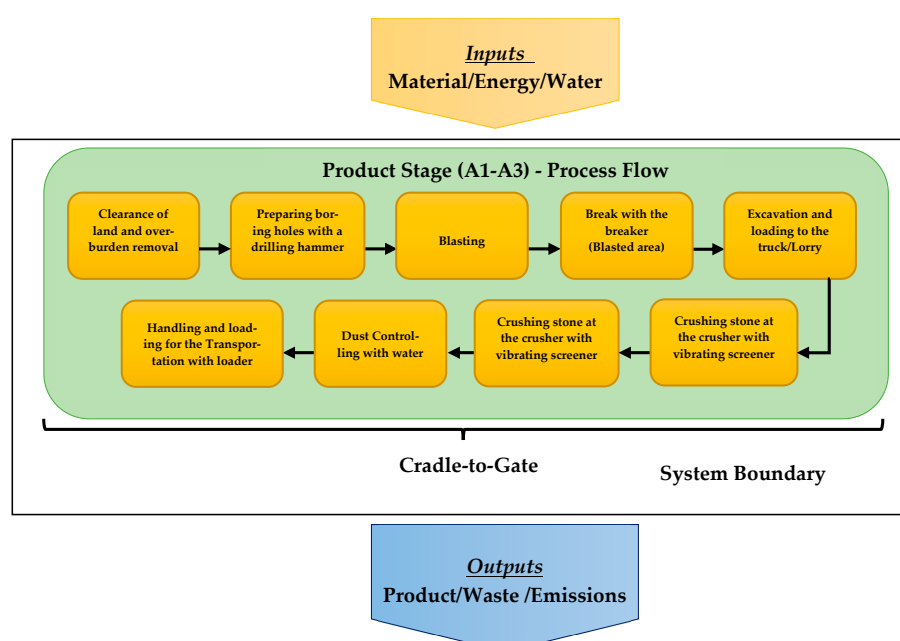


Figure 3. System boundary of rock aggregate extraction and crushing process.

2.1.2. Preparation of LCI

The LCI for rock aggregate extraction and crushing was prepared using data meticulously collected firsthand during the case analysis through comprehensive site visits. These site-specific data, gathered from utility bills, production records, purchasing orders, and invoices, ensure an accurate reflection of the LCI inventory preparation.

2.1.3. Environmental Impact Assessment

The impact assessment was performed using SimaPro 9.6 LCA software. This study used the ReCiPe 2016 Midpoint (H) impact assessment method. ReCiPe offers an advanced technique to convert LCI data into a limited range of life cycle impact scores at midpoint and endpoint levels [38]. A total of 17 out of 18 midpoint environmental impact categories were selected for interpretation and evaluation of environmental impacts [39]. These categories include mineral resource scarcity, stratospheric ozone depletion, marine eutrophication, water consumption, ionizing radiation, fine particulate matter formation, terrestrial acidification, global warming potential (GWP), ozone formation (impacting human health and terrestrial ecosystems), fossil resource scarcity, freshwater eutrophication, terrestrial ecotoxicity, marine ecotoxicity, freshwater ecotoxicity, human non-carcinogenic toxicity, and human carcinogenic toxicity. Furthermore, the CML-IA Baseline 3.08 method was also used for the characterisation of the impact of production of natural aggregates, facilitating robust comparison with finding from previous studies. This method has been widely utilized in the assessment of impacts in similar studies.

3. Results

The primary objective of this study is to estimate the potential environmental impacts of natural rock coarse aggregate production, including extraction and crushing. Accordingly, the environmental impacts of each sub-process were quantified to identify environmental impact hotspots in sub-processes.

3.1. LCI for the Natural Coarse Aggregate Production

All materials, energy and water consumption and overburden removal are presented based on the declared unit in the Table 1. In this study, the quarry operation process ends with producing three sizes of coarse aggregate and quarry dust as manufactured sand.

Table 1. LCI of the natural aggregate production process (values are presented per declared unit).

No.	Process	Input	Unit	Amount/kg	Output	Unit	Amount/kg
1	Clearance of Land and Overburden Removal	Diesel for Loader	L	4.39×10^{-4}	Removed Overburden	kg	3.62×10^{-4}
		Diesel for Lorry/Truck	L	4.39×10^{-5}			
2	Preparing boring holes with a drilling hammer	Diesel-Compress	L	8.37×10^{-5}			
		Gearbox oil-Hammer	L	1.89×10^{-6}			
3	Blasting	Ammonium Nitrate	g	2.26×10^{-5}			
		Black/Gun Powder	g	1.07×10^{-6}			
		Diesel	L	2.26×10^{-6}			
4	Break with the breaker (Blasted area)	Diesel	L	6.52×10^{-5}			
5	Excavation and load into the lorry	Diesel	L	1.44×10^{-4}			
6	Transport into the Crusher and unload to the Hopper	Diesel	L	5.51×10^{-5}			
7	Crushing Plant-Crusher 1	Electricity	Wh	1.94			
	Crushing Plant-Conveyor Belt						
	Crushing Plant-Crusher 2						
	Crushing Plant-Conveyor Belt						
	Crushing Plant-Vibrating Screener						
8	Dust Controlling with Water	Water	L	1.68×10^{-1}			
9	Handling and loading for the transportation with a loader	Diesel	L	1.19×10^{-4}			

Aggregate size and shape influence the bond strength between cement and aggregates [40]. Accordingly, the data collected from a quarry that was employed in this study yield three distinct types of coarse aggregate based on the size, which are 3/4 inches, 1 1/2 inches, chip (less than 1 1/2 inches), and quarry dust (Q-dust) as fine aggregate. Accordingly,

Table 2 shows the monthly average production of three sizes of aggregates and quarry dust as a by-product.

Table 2. Monthly Production of each type of aggregate.

Type	Monthly Average Production in kg
3/4 inches Aggregates	1350
1 1/2 inches Aggregates	135
Chip Aggregates	405
Quarry Dust	810

In the study in Ref. [2], the life cycle of natural aggregates encompasses the extraction of raw materials from the quarry, including the acquisition and transportation of explosives, as well as the processing and production stages, such as energy consumption and equipment use. According to the LCI data in Table 1, The current study reveals higher water (0.1680 L/kg) and electrical energy consumption (1.940 kW/kg) compared to Ref. [2], who conducted their study in the province of Córdoba, Spain and reported lower figures for both (water: 0.006 L/kg; electrical energy: 0.93889 kW/kg). These differences are likely due to the water consumption for the dust suppression and the efficiency of the crushing equipment. Despite this, the current study has a lower diesel consumption rate (0.00095 L/kg) compared to Ref. [2] (0.02856 L/kg), suggesting reduced GWP and fossil fuel depletion, potentially due to shorter transportation distances in the studied scenario.

3.2. Environmental Profile of the Aggregate Production Process

Figure 4 illustrates the environmental impact profile of the aggregate production process, providing a detailed analysis of the environmental consequences at each stage of the aggregate production process. Notably, within the aggregate production process, the “crushing stone” stage emerges as a significant hotspot for adverse environmental impacts, contributing substantially a cross all assessed categories. The primary impacts of the crushing stone process include human carcinogenic toxicity, freshwater eutrophication, and marine eutrophication. The stage of removing overburden is the second highest contributor to environmental damage, with significant impacts on fossil resource scarcity, freshwater eutrophication, and human carcinogenic toxicity (refer to Figure 4). Dust control shows a noticeable impact on the water consumption category, with almost zero contributions across other categories. The processes of excavating rock and handling aggregate show similar environmental impacts, having relatively low contributions across various categories such as water consumption, mineral resource scarcity, marine eutrophication, human non-carcinogenic toxicity, and ionizing radiation but exhibiting notable impacts in fossil resource scarcity and freshwater eutrophication. The processes of drilling, blasting, breaking, and transporting broken rock exert low environmental impacts, contributing only marginally across several categories such as mineral resource scarcity, marine eutrophication, human non-carcinogenic toxicity, and ionizing radiation. Their overall environmental impact within the natural aggregate production process remains insignificant.

3.3. Normalisation Results of All Impacts

As the characterised analysis does not directly reveal the extent of influence of individual impact categories on the overall environmental impact, a normalised analysis was conducted. Figure 5 presents the normalised values (Pt) for different impact categories, showcasing how sub-processes contribute to each category. It is evident that among these categories, “human carcinogenic toxicity” stands out as the most significant impact linked to gravel production (refer Figure 5). Notably, the subprocess of crushed stone extraction significantly contributes to this specific impact category. Considering the aggregate impact contribution, “human carcinogenic toxicity” accounts for nearly half of the overall environmental impact with 2.45938×10^{-6} Pt. This substantial influence can be attributed to the noteworthy electricity consumption associated with the process. “Freshwater eutrophica-

tion” has the second highest environmental impact with 1.59326×10^{-6} Pt, and the “Fossil resource scarcity” with 1.4823×10^{-6} Pt is the third-highest environmental impact category. “Mineral resource scarcity” has the lowest environmental impact with 2.62×10^{-12} Pt as shown in Figure 5.

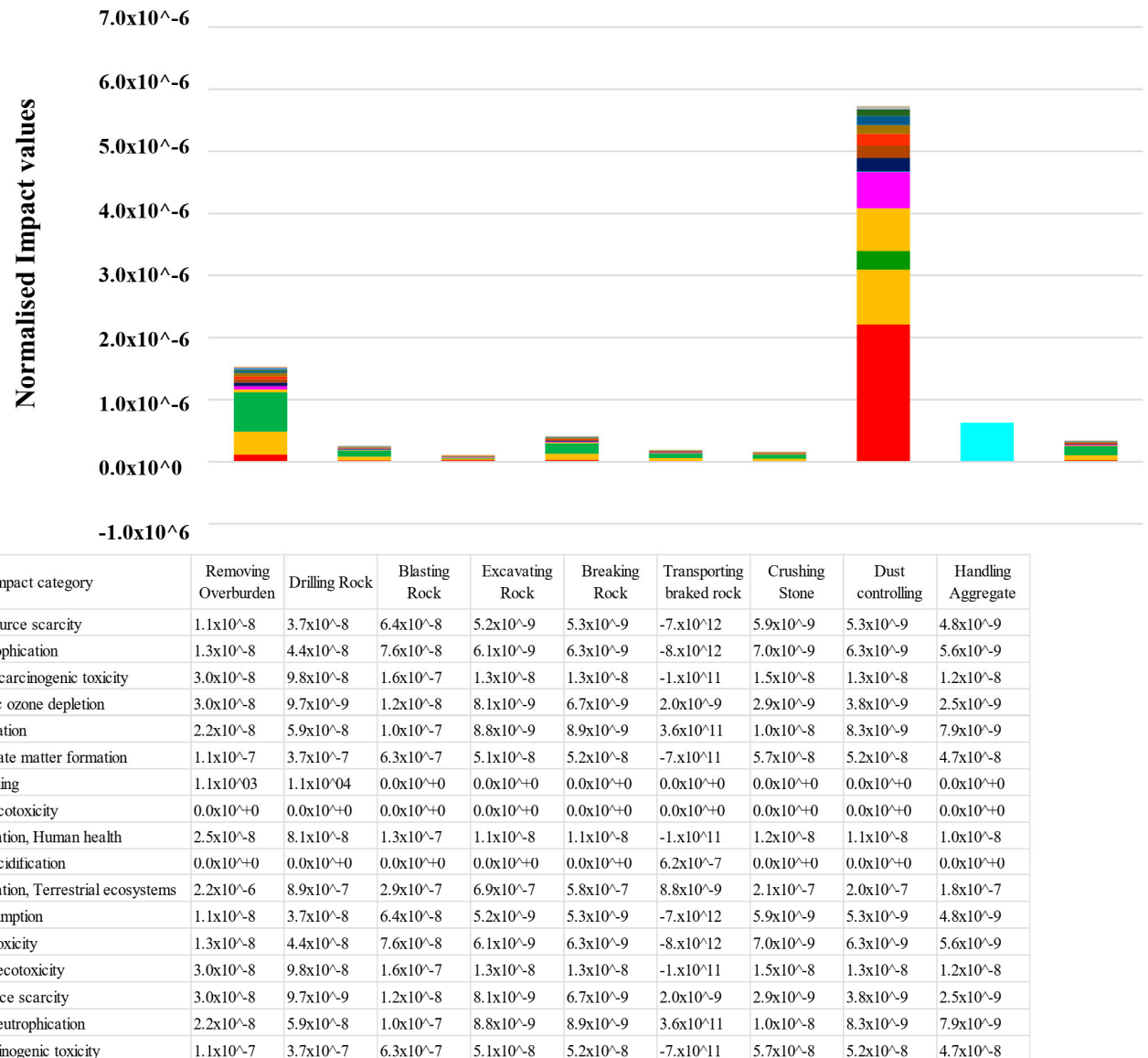


Figure 4. Environmental profile of different stages in the processes of natural aggregate production. Normalized impact values in points are given for the production of 1 kg of natural aggregate.

3.4. Characterisation Results of All Impacts

According to Figure 6, the subprocess of crushing the excavated rock has the highest environmental impact across most impact categories. In contrast, water used for dust control has the highest impact on the category of water consumption. The reason behind the high impact associated with the process of crushing the excavated rock is the high electricity consumption for the crusher operation. The overburden removal process is also associated with a significant impact on stratospheric ozone depletion, terrestrial ecotoxicity, mineral resource ecotoxicity, and fossil resource scarcity, mainly due to the fossil fuel consumption associated with the process.

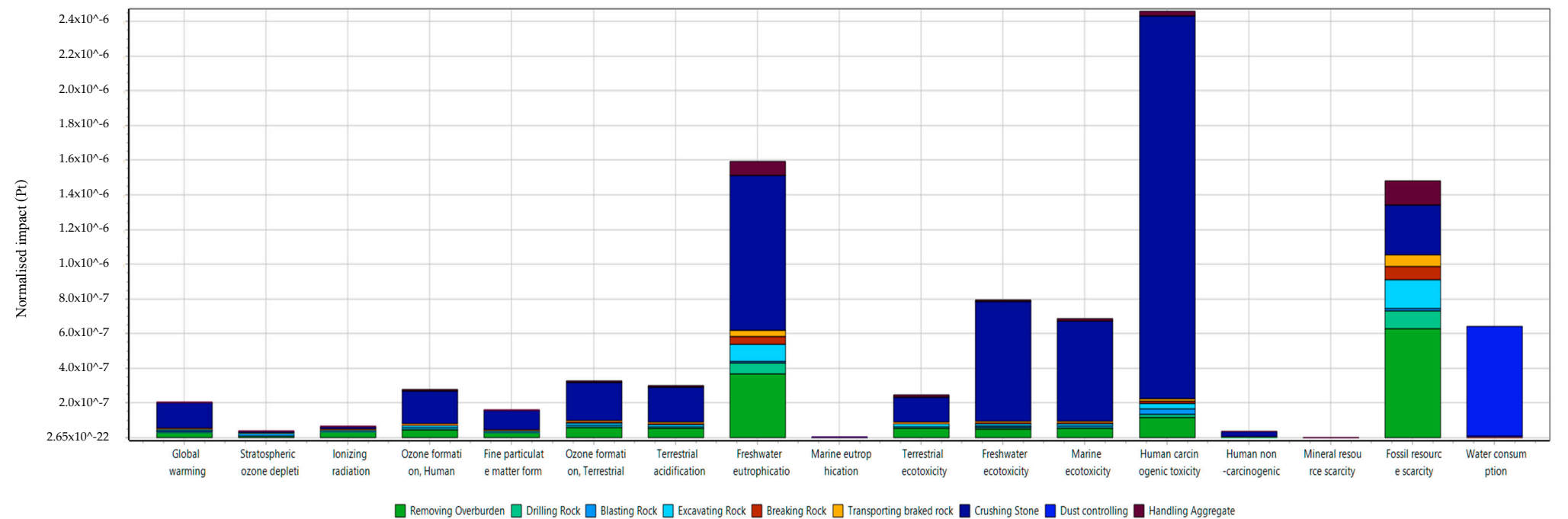


Figure 5. Normalised mid-point impacts of natural rock coarse aggregate for 1 kg of production.

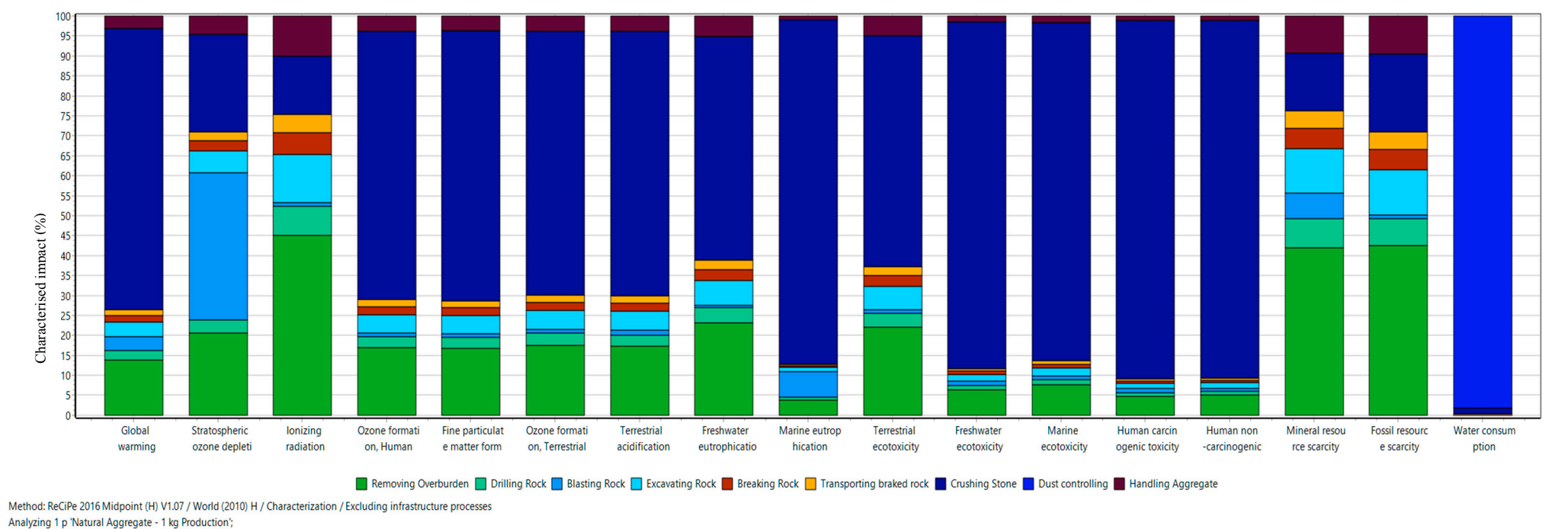


Figure 6. Characterised mid-point impacts from 1 kg of natural rock coarse aggregate.

3.5. Interpretation of the Characterised Results of Key Mid-Point Impacts

The subsequent sections present and interpret the environmental impact contribution of producing 1 kg of coarse aggregate across various notable impact categories. The interpretation is derived from the characterisation values reflecting the process-specific contribution to adverse environmental impact in each impact category. The process contribution analysis helps pinpoint the significant processes influencing the outcomes, enabling a targeted approach to mitigate environmental harm. The contribution analysis results clarified the combined contributions from individual processes [41].

According to Figure 4, the rock-crushing process contributes to the highest environmental impact regarding human carcinogenic toxicity, specifically 2.21071×10^{-6} kg 1,4-DCB, marking it as the most significant process. According to this study's life cycle impact assessment (LCIA) results, "hard coal mining associated waste generation" is the main reason behind the human carcinogenic toxicity, and it is the highest single process contribution, with 1.02768×10^{-7} kg 1,4-DCB. According to [42], extensive utilisation of coal for power generation in many countries due to its high energy generation potential leads to the emission of significant pollutants such as CO_x, SO_x, NO_x, PM, and heavy metals, impacting human health and the environment. The primary factor contributing to human carcinogenic toxicity is chromium discharge into water, accounting for an overwhelming 97.31% of the contribution in coal mining in China [41]. Coal deposits contain minerals, such as arsenic and silica, known to be carcinogenic to humans [43]. In Sri Lanka, the electricity generation mix in 2016 included 35% imported coal, highlighting the significant coal intensity of the electricity grid [44]. Consequently, the reliance on coal within Sri Lanka's electricity generation mix exacerbates these detrimental effects.

The crushing process significantly influences the freshwater eutrophication impact category, ranking as the second-highest category affected with 1.03×10^{-6} kg P eq. During the production process of natural aggregate, emissions of substances like SO₂, H₂SO₄, and NO₃ significantly contribute to eutrophication [25]. Based on the life cycle impact assessment process-wise contribution results, the "spoil from hard coal mining (treated in surface landfill)" and "spoil from lignite mining (treated in surface landfill)" are closely associated with electricity generation, making substantial contributions to freshwater eutrophication at approximately 1.67714×10^{-6} kg P eq and 6.06625×10^{-7} kg P eq, respectively. According to [45], coal is the most environmentally harmful fuel for eutrophication, with an impact of 1.9 g of PO₄ 3-equivalent per kilowatt-hour (kWh). This impact is more than twice the impact of oil, which is 0.8 g of PO₄ 3-equivalent per kWh and ten times greater than gas, which has an impact of 0.2 g of PO₄ 3-equivalent per kWh. The coal-intensive electricity grid in Sri Lanka is the primary reason behind the high freshwater eutrophication associated with its power generation. Furthermore, during the pulverisation of collected rocks, energy in the form of diesel and electricity is consumed, leading to the emission of ammonia (NH₃), ammonium, phosphate, and nitrogen oxide [25]. Similarly, in this study, the contribution of petroleum consumption to freshwater eutrophication ranks second after coal-related impacts, amounting to 6.2584×10^{-7} .

Furthermore, freshwater ecotoxicity is impacted substantially by zinc discharge in coal mining, followed by vanadium, copper, and nickel [41]. According to the LCIA results in this research, spoil from hard coal mining and lignite mining are the prominent contributors to freshwater ecotoxicity. As a subprocess, rock crushing also significantly impacts the freshwater ecotoxicity category. Therefore, it can be assumed that the coal intensity of the country's grid mix is the underlying reason for this freshwater ecotoxicity. According to the LCIA results of the study, the impact contribution is dispersed across all processes utilising "hard coal" and "petroleum" as an energy source, making fossil resource scarcity the third highest environmental impact category. When examining individual processes, the highest contributions come from hard coal mining operations (4.77852×10^{-7} kg oil eq), petroleum and gas production (3.4×10^{-4} kg oil eq), and petroleum production (3.45829×10^{-7} kg oil eq). The petroleum production process significantly contributes to the depletion of fossil fuels when compared to other impact categories, mainly because petroleum, classified as a fossil fuel, is used as a primary raw material in the extraction process [46]. Accordingly, this study's main reasons for

resource depletion are electricity consumption from a coal-based grid and petroleum-related fuel consumption for transportation and grid-electricity generation. Furthermore, freshwater ecotoxicity is impacted substantially by zinc discharge in coal mining, followed by vanadium, copper, and nickel [41]. According to the LCIA results in this research, spoil from hard coal mining and lignite mining are the prominent contributors to freshwater ecotoxicity. As a subprocess, rock crushing also significantly impacts the freshwater ecotoxicity category. Therefore, it can be assumed that the coal intensity of the country's grid mix is the underlying reason for this freshwater ecotoxicity.

According to this study, “hard coal” and “lignite mining waste” are the two main processes contributing to marine ecotoxicity—in that order—with 8.96033×10^{-7} kg 1,4-DCB and 2.79419×10^{-7} kg 1,4-DCB. Using steel as a supporting material in the coal industry is the leading cause of ecotoxicity in maritime environments [41]. Furthermore, coal mines generate massive amounts of wastewater each year. Over 80% of the wastewater is dumped straight into the environment without being treated or recycled, which results in marine ecotoxicity [41]. “Hardwood-related processes” contribute 7.54181×10^{-9} kg 1,4-DCB to the aggregate production associated with marine ecotoxicity. Cleft timber (measured as dry mass) as a raw material for charcoal production, a key ingredient in gunpowder/black powder utilised in the rock blasting process, is the primary contributor to marine ecotoxicity suggested to be the reason [47]. The energy used in every stage of production, from removing overburden to loading to transporting off-site, involves various processes such as drilling, blasting, primary crushing, surge stockpiling, conveying, crushing, screening, final stockpiling, and loading to transport off-site [48]. The findings of the research conducted by [49] emphasise that environmental impacts are predominantly influenced by rock grinding rather than rock mining [49]. Similarly, this study has the highest overall environmental impact associated with rock-crushing.

4. Discussion

Table 3 compares the findings of this study with those of three earlier studies carried out in Europe by [27], in Korea by [28], and in Hong Kong by [27] in terms of the extraction and crushing of natural coarse aggregates. According to this research, the potential for abiotic depletion is 1.95059×10^{-10} kg Sb eq. Compared to this study, the other three studies demonstrated a higher impact. However, Ref. [28] observed a more significant depletion at 3.82×10^{-4} kg Sb eq. This study measured the GWP-related emissions at 1.61×10^{-3} kg CO₂ eq, notably lower than the emissions reported in three prior studies. The highest GWP in the study by [3,18], produced in Hong Kong, is mainly due to the extensive transport distances [50]. For instance, Ref. [50] reported 4.3×10^{-3} kg CO₂ eq emissions. The high GWP can be attributed to emissions from coal combustion in thermoelectric power plants that generate electric energy.

Moreover, fluctuations in transportation distances also impact variations in GWP in the aggregate production process [51]. The ozone depletion potential (ODP) result was 6.39×10^{-10} kg CFC–11 eq, comparable to the results from the last three investigations. The utilisation of liquefied natural gas and coal energy in manufacturing leads to emissions of sulfur dioxide (SO₂), sulfuric acid (H₂SO₄), and nitrate (NO₃–), which contribute to ozone depletion [28]. Changes in relevant energy consumption accordingly led to variations in ODP. Furthermore, the production of explosives primarily impacts ODP [21]. The photochemical oxidation is relatively low at 5.51×10^{-7} kg PO₄ eq in this research study, and it is still lower than studies conducted in Refs. [27,49] (refer Table 3).

Table 3. Comparison of aggregates' environmental impact with previous studies.

Impact Category	Unit	This Study	[27]	[49]	[3]	[52]
Abiotic depletion	kg Sb eq	1.85×10^{-10}	1.09×10^{-9}	3.82×10^{-4}	N/A	1
GWP	kg CO ₂ eq	2.93×10^{-3}	2.44×10^{-2}	1.43×10^{-2}	3.20×10^{-2}	2.11
ODP	kg CFC–11 eq	6.39×10^{-10}	2.43×10^{-10}	3.06×10^{-10}	9.88×10^{-10}	N/A
Photochemical oxidation	kg C ₂ H ₄ eq	5.51×10^{-7}	7.83×10^{-6}	1.41×10^{-5}	N/A	5.00×10^{-4}
Acidification	kg SO ₂ eq	1.45×10^{-5}	1.44×10^{-4}	1.98×10^{-5}	1.90×10^{-4}	2.10×10^{-2}
Eutrophication	kg PO ₄ eq	5.93×10^{-6}	3.18×10^{-5}	3.67×10^{-6}	7.00×10^{-7}	3.00×10^{-3}

Similar effects on acidification were noted in this research study (1.45×10^{-5} kg SO₂ eq) compared with studies conducted in Ref. [49]. Two other studies, Refs. [3,27], show similar impacts with each other (refer Table 3). The combustion of fuel and the use of ammonia-based explosives for raw material extraction are significant contributors to eutrophication [53], and fossil fuel production also significantly influences the potential for eutrophication [54]. The effects of eutrophication were comparable to those reported by [49], with values of 5.93×10^{-6} kg PO₄ eq and 3.67×10^{-6} kg PO₄ eq, respectively. However, Ref. [27] showed a considerably higher unit value (3.18×10^{-5} kg PO₄ eq), and [3] (2016) showed a lower value (7.00×10^{-7} kg PO₄ eq.).

The results obtained from Ref. [52], which investigated various concrete grades incorporating both natural and recycled aggregates, demonstrate significantly elevated levels of GWP, acidification, and eutrophication in natural aggregate production compared to prior research. For example, Ref. [52] state a GWP of 2.11 kg CO₂ equivalent, notably greater than the values documented in this study and other investigations. Likewise, their levels of acidification and eutrophication are significantly increased, suggesting a greater environmental impact linked to their overall production processes. The use of explosives and electricity significantly impacts the ODP and transportation highly impact on GWP [2].

The discrepancies in environmental impact findings among these studies can be attributed to variations in local energy sources, production methods, and methods of extracting raw materials. Differences in the composition of energy sources, such as using coal as opposed to cleaner alternatives, impact GWP and ODP. Regional variations in production processes and transportation distances significantly impact the photochemical oxidation and acidification process. Furthermore, discrepancies in the utilisation of fuel types and the use of ammonia-based explosives are factors that contribute to divergent consequences in eutrophication.

Enhancing Environmental Sustainability in Natural Rock Aggregate Production Process

This LCA study has revealed critical hotspots within the production process, thereby identifying potential opportunities for environmental improvements. Accordingly, drawing upon the findings from existing literature, this section seeks to elevate the environmental sustainability of the natural aggregate production process by addressing the identified hot spots of environmental impact.

The rock-crushing process significantly contributes to environmental impacts across all discussed categories, primarily due to coal consumption from the Sri Lankan electricity grid. It is crucial to acknowledge the pivotal role of the selected electricity mix in achieving electricity savings. Hence, opting for electricity sourced from hydropower, which inherently has lower impacts on GWP than fossil fuels, would yield substantial environmental improvements in the natural rock aggregate manufacturing process [55]. Ref. [56] revealed that introducing a Solar PV plant into an aggregate manufacturing facility led to significant reductions, ranging from 30% to 50%, in impacts related to GWP, eutrophication, acidification, human toxicity, and other categories. Therefore, implementing a solar PV plant emerges as a more effective solution for curbing emissions associated with the high electricity consumption in the rock-crushing process.

This study overlooked the impact of assets on environmental outcomes in aggregate production, an essential aspect to explore. This omission is significant, especially amid ongoing discussions about advancing new, more efficient, and environmentally sustainable machinery, particularly for transportation and crushing processes [55]. Furthermore, optimising parameters for energy consumption in grinding machines is key for recommending environmental consciousness. Grinding machine design depends highly on the material being crushed and the degree of grinding required [57]. Ref. [58] indicates that adjusting crusher settings can significantly influence the energy consumption of the crushing process. Considering that improved fragmentation reduces energy consumption during the crushing process, it is crucial to factor in blasting parameters when designing blasting operations to achieve raw material fragmentation [59].

Producing recycled aggregates can reduce net environmental impacts by approximately 49–51%, thereby significantly enhancing sustainability in the natural rock aggregate production process [3], and reducing the industry's dependence on natural aggregates [60]. Substituting natural aggregate with a higher proportion of recycled aggregate led to a decrease in acidification and eutrophication indices of up to 40% [25]. This change highlights the benefits of transitioning to recycled aggregates, which greatly improve environmental sustainability in the production process of natural rock aggregates. The certification of the coarse aggregate production process, implementing standards like the ISO 14044, ensures that an organisation minimises environmental damage and consistently improves its environmental performance [1]. These standards establish a structured approach to effectively managing and enhancing environmental impact at every stage of the production process.

The insufficient oversight of aggregate resources and their extraction results in unsustainable urban development [61]. Accordingly, To advance the aggregate production process, it is imperative to establish new specifications and standards that prioritize environmental and sustainability concerns alongside traditional parameters [62]. According to Ref. [63], a mega quarry is favoured over numerous small quarries to mitigate the adverse impacts of quarry mining operations [63]. The environmental footprint of natural aggregates is generally considered to be higher than that of some alternative materials, particularly recycled aggregates and industrial by-products. Natural aggregate production involves significant environmental impacts, such as habitat disruption from quarrying, high energy consumption, and greenhouse gas emissions during extraction, crushing, and transportation processes. In contrast, alternative materials like recycled aggregates typically have a lower environmental footprint due to the reduced need for raw material extraction and energy-intensive processing. Conversely, according to [64], the environmental impacts associated with recycled aggregate production are slightly higher than those of natural aggregate and the increase varies between 11.3% and 36.6%, depending on the impact category. Moreover, the use of industrial by-products as substitutes for natural aggregates can further decrease environmental impacts by diverting waste from landfills and reducing the demand for virgin resources. The advantages of recycling, especially in terms of reducing waste and preservation of natural mineral resources, are clear [64].

5. Conclusions

In Sri Lanka, coarse aggregate production is fulfilled by rock aggregate. The rock-crushing process also replaces the partial completion of the requirement of fine aggregate with quarry dust. Furthermore, coarse aggregate is one of the widely used materials. The natural rock aggregate production process is energy-intensive, especially for crushing blasted rock into required sizes and diesel consumption as a fuel in operating heavy machines such as rock breakers, loaders and trucks for transportation and handling purposes.

Accordingly, there is a potential need to quantify and evaluate the environmental impact associated with the process with LCI and LCIA data. However, there is no country-specific environmental impact assessment data for the natural rock aggregate production in Sri Lanka. This study provides a comprehensive dataset spanning various environmental impact categories, encompassing the sub-processes inherent to the natural rock aggregate production process. This dataset serves as a valuable resource for underpinning forthcoming environmental impact assessments in the context of construction projects. Furthermore, environmental hotspot identification will potentially guide manufacturers in determining areas of focus for environmental improvements in the future.

According to the research findings, a significantly high environmental impact on “human carcinogenic impact” is associated with the natural rock aggregate production process, and the reason behind this is the human carcinogenic releases at the hard coal production. Furthermore, “freshwater eutrophication”, “freshwater ecotoxicity”, and “fossil resource scarcity” have considerable environmental impact categories. The reason behind these impacts is also linked to the hard coal mining and production process used for electricity production and petroleum mining and refining processes. Almost 27% of the overall impact

is due to the “human carcinogenic impact”, while “freshwater eutrophication” is approximately 17%, “fossil resource scarcity” is approximately 15%, and “freshwater ecotoxicity” is approximately 9%. Additionally, in a comprehensive analysis, the total impact of this study is far lower than that of other studies focusing on the production of natural aggregate in different regions around the world. The lower overall environmental impact in Sri Lanka’s natural rock aggregate production might be mainly due to reduced reliance on coal-based electricity compared to other regions. Additionally, localised practices such as shorter transportation distances from rock extraction sites to crushers and more efficient water usage in dust suppression could contribute to this reduced impact.

The primary environmental impact of natural rock aggregate production, primarily attributed to rock crushing, stems mainly from the substantial electricity consumption inherent in the process. These findings underscore the significant challenge posed by energy consumption within the industry, particularly in Sri Lanka, given its reliance on a coal-based electricity grid. Regulation and policy play a critical role in minimizing the environmental impact of aggregate production. Stringent environmental regulations can drive the adoption of more sustainable practices in the aggregate industry, such as the implementation of cleaner production technologies, the use of renewable energy sources, and the enhancement of recycling rates. Policies that promote the use of alternative materials, such as recycled aggregates or industrial by-products, can further reduce the environmental footprint of the construction industry.

Consequently, recommending alternative cleaner energy sources emerges as a viable solution. Accordingly, it is further recommended to compare conventional versus cleaner energy scenarios as a future research direction. Additionally, a comparative analysis of recycled and natural aggregates should be conducted to assess their environmental and economic benefits. Finally, a comprehensive social and economic life cycle assessment (LCA) is essential to evaluating the broader impacts of different production methods, guiding more informed and sustainable decision-making. Furthermore, exploring sustainable natural rock aggregate production strategies warrants further investigation. Furthermore, further research is recommended to assess the potential for improvements and explore additional alternatives. Conducting a social life cycle assessment (SLCA) and applying material flow cost accounting (MFCA) would provide valuable insights into the social and economic implications of the aggregate production process.

While the research is based on a specific case study in Sri Lanka, the methodologies employed—such as the environmental impact assessment techniques, lifecycle analysis, and the identification of environmental hotspots—are applicable to similar aggregate production processes worldwide. The environmental impacts of aggregate production are influenced by factors such as energy sources, production technologies, and raw material availability, which can vary across different countries. However, the fundamental principles underlying the environmental footprint of crushed natural aggregates, as well as the identified opportunities for enhancing sustainability, are broadly relevant. By considering the local environmental, economic, and regulatory conditions, these findings can be adapted to other regions with similar industrial practices. Additionally, the study provides a framework that can be used by policymakers and industry professionals in other countries to conduct similar assessments and implement sustainable practices in aggregate production. This approach not only contributes to the global understanding of the environmental impacts associated with construction materials but also offers actionable insights for reducing the environmental footprint in diverse contexts.

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