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Identifying key attributes driving the environmental performance of aggregate production

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Abstract

Current design practices for aggregate production plants primarily focus on operational and economic viability. To reach Sustainable Development Goals (SDGs), there is a need to improve the environmental performance of production plants, which requires incorporating environmental aspects into design practice for both current and future plants. However, beyond energy and water management, stakeholders have limited guidance for integrating environmental performance into design and operational decisions informed by real-world data from operational plants. In this study, Life Cycle Assessment has been used to calculate the environmental impacts of 16 aggregate production plants in Europe based on site-specific data. The results are explored to benchmark and identify key site-specific characteristics associated with high and low environmental performance. The findings aim to provide evidence-based insights to inform current and future plant design and support the development towards low-impact production systems.

Keywords: Aggregate Production, Environmental Performance, Life Cycle Assessment, Data-driven Assessment.

1. Introduction

A central challenge for the extraction industry is the ability to quantify environmental impacts in a way that supports meaningful operational improvements over time. Life Cycle Assessment (LCA) has emerged as a key approach for evaluating the environmental performance of extraction industries (Segura-Salazar et al., 2019). Through LCA, stakeholders involved in the extraction industry can identify the operations that significantly affect their environmental performance, monitor how impacts change over time, and produce standardized Environmental Product Declarations (EPDs) to communicate environmental data on extraction products, particularly aggregates from quarrying. The rapid increase in EPDs for aggregate products over the past decade means that more environmental data from quarrying operations is available today than ever before (EPD International, 2026).

Furthermore, several academic studies have applied LCA to evaluate the environmental performance of aggregate products produced from primary and secondary sources (de Bortoli, 2023; Gowda et al., 2024; Lee et al., 2024; Martinez-Arguelles et al., 2019; Rosado et al., 2017; Simion et al., 2013). Across these studies, diesel consumption consistently emerges as a major contributor to impacts, with explosives also highlighted in some cases. Nevertheless, a key finding in the literature is the wide variation in reported impacts across sites, indicating that dominant impact sources depend on site-specific characteristics.

In parallel, there is a growing societal interest in designing more sustainable aggregate production plants to secure Europe's future raw material supply and comply with regulatory frameworks such as the Corporate Sustainability Reporting Directive (CSRD) (Vera-Burau et al., 2025). However, sustainability considerations are often introduced late in the planning process through Environmental Impact Assessments (EIAs), where the focus tends to be on mitigating identified impacts rather than minimizing them through proactive design measures beyond operational efficiencies, such as fuel and water optimization (Muñoz et al., 2014).

Recent research, therefore, emphasizes the need to integrate sustainability earlier in the planning process, proposing approaches such as ESG-driven criteria, sustainability-enhanced block models, and stakeholder-informed design (Asr et al., 2019; Laurence, 2011; McLellan et al., 2009; Vera-Burau et al., 2025). Yet the use of LCA data to inform site design from a data-driven approach remains largely unexplored.

This study addresses this gap by combining environmental performance data estimated using LCA for 16 aggregate production plants (sites) with detailed information on site-specific characteristics (attributes) related to geography, operational, and design. The aim is to estimate environmental performance across sites and to explore which site attributes are associated with lower or higher environmental impacts. Using descriptive statistics, namely the arithmetic mean and range, and visualizations of distribution, is used to identify trends and potential associations between environmental performance and different attributes.

2. Methodology

Attributes with a potential influence on environmental impact were identified through an internal workshop with researchers involved in three European research projects concerning the environmental performance of operations involved in aggregates and mineral production; specifically, DigiEcoQuarry, EPD-Berg, and ROTATE (DigiEcoQuarry, 2024; EPD Berg, 2025; ROTATE, 2024). A total of 16 sites located across Europe have been considered for the study and have been classified into three categories based on their annual production volume, as seen in Table 1.

Table 1: Site categorization based on production volume.

Category	Production volume (tonne/year)	Number of sites
Low	≤ 250,000	4
Medium	250,000 – 500,000	5
High	500,000	7

To quantify the environmental performance for each production volume category, an LCA based on EN 15804+A2 (Svensk Standard [SIS], 2021) was conducted for 16 sites by utilizing site-specific data collected over a period of 1 year. The LCA studies were conducted using an industry-specific EPD tool in the online platform, *PlantSmith* (Asbjörnsson et al., 2024; Roctim, 2026). A declared unit of 1 tonne of aggregate, representing the average product from the site, has been used to facilitate comparability. Only cradle-to-gate impacts have been included in the study for comparison due to uncertainties surrounding scenario-based results for later life-cycle stages (transport to customer, installation, use, & end-of-life). Therefore, results are included for extraction (A1), transportation from the extraction site to the production site (A2), and production (A3), i.e., comminution and classification process. To facilitate comparison of the environmental performance, the same background database (PlantSmith Ecoinvent Database 26.1) and Life Cycle Impact Assessment (LCIA) method (Environmental Footprint 3.1) have been used for all sites. Within this study, the environmental performance is represented by 6 core impact categories: Global Warming Potential (GWP) - total, Abiotic Depletion Potential (ADP) - fossil, Acidification Potential (AP), Water Depletion Potential (WDP), Eutrophication Potential (EP) - freshwater, and Ozone Depletion Potential (ODP).

For each production volume category, environmental performance has been investigated using descriptive statistics, namely arithmetic mean and range (minimum and maximum), and visualization of distribution to explore the possible relationship between the performance and different attributes.

3. Results

A total of 83 attributes were identified for each site. These attributes were grouped into three categories, namely, geographical, operational, and design. Geographical attributes include site location, deposit depth, and carbon intensity of electricity grid mix. Operational attributes include resource consumption (e.g., diesel, electricity, explosives, metals, water, and rubber), production (e.g., yearly production

quantity and operating hours), and waste generation. Design attributes include extraction (e.g., technique, main power source), transportation (e.g., number of yellow machines, distance from extraction to processing site, main power source, transport mode), and processing circuit (e.g., type, main power source, number of product fractions produced, crushing stages, number of crushers, and screens). This paper primarily focuses on operational attributes.

Figure 1 presents the distribution of design attributes across three production volume categories: low, medium, and high. It can be observed that the mean production volume increases from 133,454 tonne/year in the low-volume category to 1,062,507 tonne/year in the high-volume category, representing nearly an 8 times difference. It can be observed that as the production volume increases, so does the need for the number of crushers, screens, and crushing stages, as can be seen in Figure 1. Furthermore, sites classified in the high and medium volume categories predominantly used stationary processing circuits powered by grid electricity, whereas sites in the low-volume category used mobile circuits powered by diesel. Despite the trend observed among the different production volume categories, the high-volume category shows the widest range across all attributes, as shown in Figure 1 (e.g., product fractions produced range between 5 at site 4 and 34 at site 3).

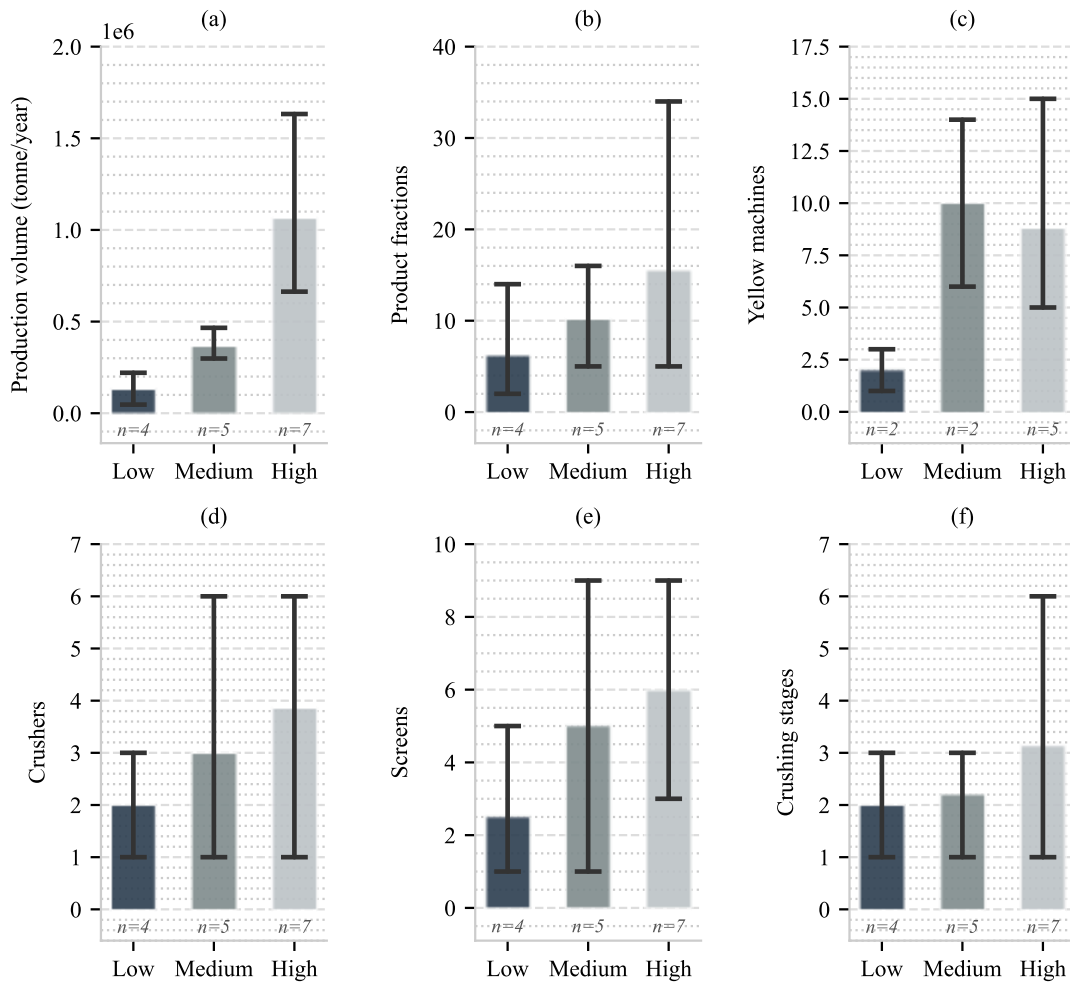


Figure 1: Mean (shown in bars) and range (minimum and maximum, shown as I) for different attributes for the three production volume categories: a) production volume, b) number of product fractions produced, c) number of yellow machines, d) number of crushers, e) number of screens, and f) number of crushing stages.

3.1 Environmental performance

Figure 2 shows the environmental performance for the three production volume categories using the mean and range across 6 core impact categories. It can be observed that environmental performance

varies across categories. The high-volume category shows a lower impact across 4 of the core impact categories. In the case of GWP-total, the low-volume category has the highest mean GWP (4.87 kg CO₂eq./tonne) and the widest range (1.77 - 12.71 kg CO₂eq./tonne). The medium and high volume categories had means of 4.11 and 3.07 kg CO₂eq./t, respectively. The GWP-total of the high-volume category (3.11 kg CO₂eq.) was 36% lower when compared with the low-volume category (4.87 kg CO₂eq.). A similar pattern is observed in the ADP-fossil and ODP impacts, where the lowest impact was recorded in the high-volume category. This indicates a possible relationship between the production volume and environmental performance.

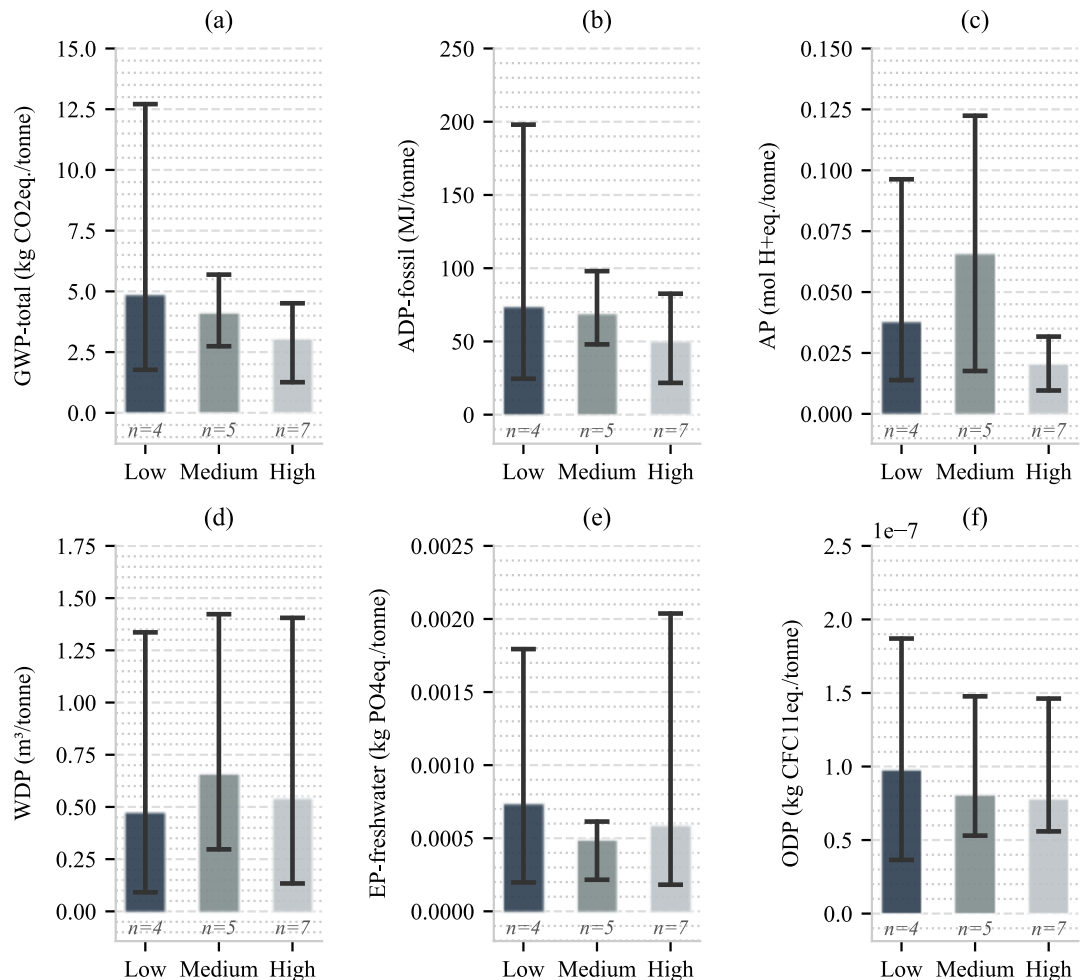


Figure 2: Mean (shown in bars) and range (minimum and maximum, shown as I) results in 6 of the environmental impact categories examined across different production volume categories per tonne of product: (a) GWP-total, (b) ADP-fossil, (c) AP, (d) WDP, (e) EP-freshwater, and (f) ODP.

To enable further investigation of environmental performance, one impact category was chosen to explore in depth, namely, climate impact in the form of GWP-total. Figure 3 shows the cradle-to-gate GWP-total for all 16 sites. It can be observed that the best performing site in the high-volume category (i.e., site 16 at 1.26 kg CO₂eq./tonne) is estimated to be 10 times lower than the worst performing site in the low-volume category (i.e., site 9 at 12.71 kg CO₂eq./tonne). This indicates the effect of economies of scale, i.e., high volume production can lead to improved efficiency and better environmental performance.

The contributions from different lifecycle stages to the cradle-to-gate GWP-total impact varied among sites for each lifecycle stage, as shown in Figure 4. To compare the three production volume categories, the mean value for each life cycle stage within each category was considered. A minor variation can be observed in the contribution from the extraction: 19%, 21%, and 22% for low, medium, and high volume, respectively. For transportation, the contribution varied significantly across the low, medium, and high

volume categories: 37%, 27%, and 47%, respectively. For production, the contribution varied across the low, medium, and high volume categories as follows: 44%, 52%, and 31%, respectively. The variation in contributions from different life cycle stages indicates that the type and size of the site could also be an influencing factor when comparing the environmental performance.

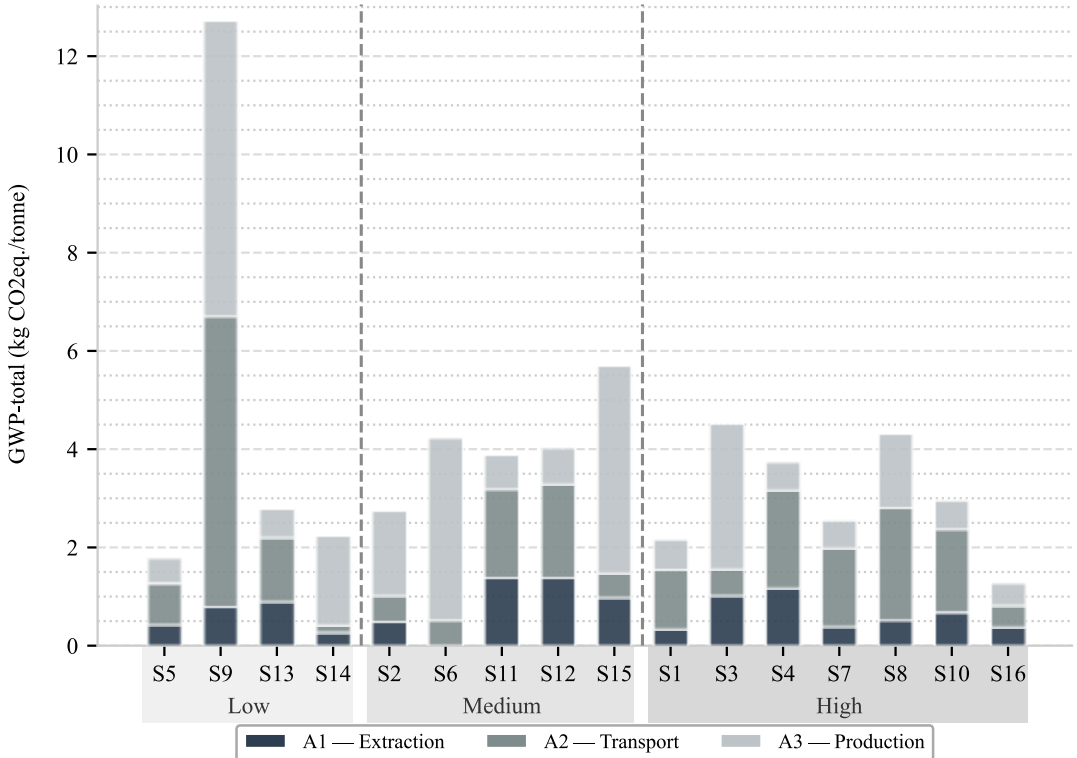


Figure 3: Variation in results for GWP-total per tonne aggregate produced across the included sites, with the lifecycle stages (A1, A2, and A3) in which the impact occurs.

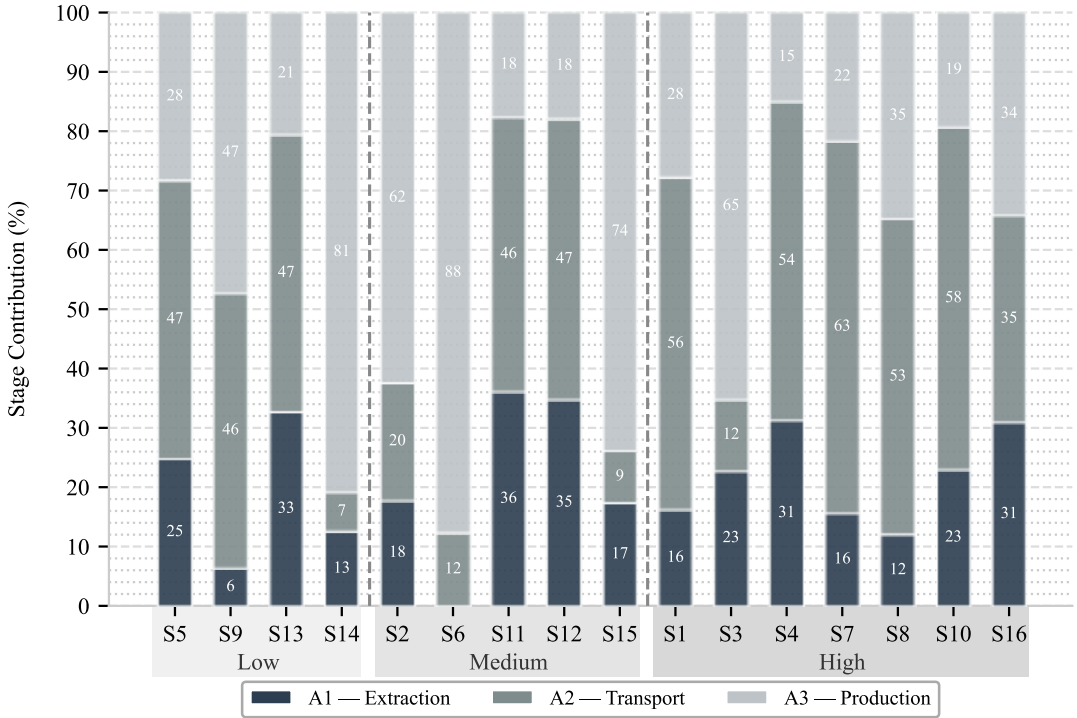


Figure 4: Percentage contribution from different life cycle stage (A1, A2, and A3) for GWP – total.

3.2 Resource consumption and contribution to impacts

To further understand the reason behind the variation in impacts, the operational attributes related to the consumption of different resources, such as diesel, electricity, explosives, metals, rubber, and water, and their contribution to environmental performance were investigated. Figure 5 shows the consumption of resources for producing 1 tonne of aggregate products per production volume category. It can be observed that electricity, explosives, and rubber consumption increase with production volume. For instance, electricity consumption increases from 0.98 kWh/tonne at low volume to 2.24 and 2.19 kWh/tonne at medium and high volume, respectively. Furthermore, sites classified in the medium and high volume categories predominantly used stationary processing circuits powered by electricity, which can explain the high electricity consumption. On the other hand, the difference in explosive consumption per tonne was minor across the production volume categories, since blasting was the predominant extraction technique used at most sites categorized as low, medium, and high. For rubber, higher consumption at medium and high volume sites may be due to the replacement of worn conveyor belts in stationary processing circuits and worn tires on yellow machines (trucks and wheel loaders).

On the other hand, diesel, metals, and water consumption show an inverse relationship with the production volume, as can be seen from Figure 5. For instance, for diesel, the low-volume category shows the highest consumption (0.97 litres/tonne), which is 48% higher than the high-volume category (0.50 litres/tonne). This is because all sites categorized as low-volume predominantly use mobile or hybrid circuits, and diesel was the main energy source for both transport and production. It should be noted that the higher mean value for the low-volume category is mainly due to the range, which was 0.34 - 2.3 litres/tonne at sites 5 and 9, respectively. For metals, consumption is in the low-volume category due to higher consumption at site 9 and can be related to low production volume.

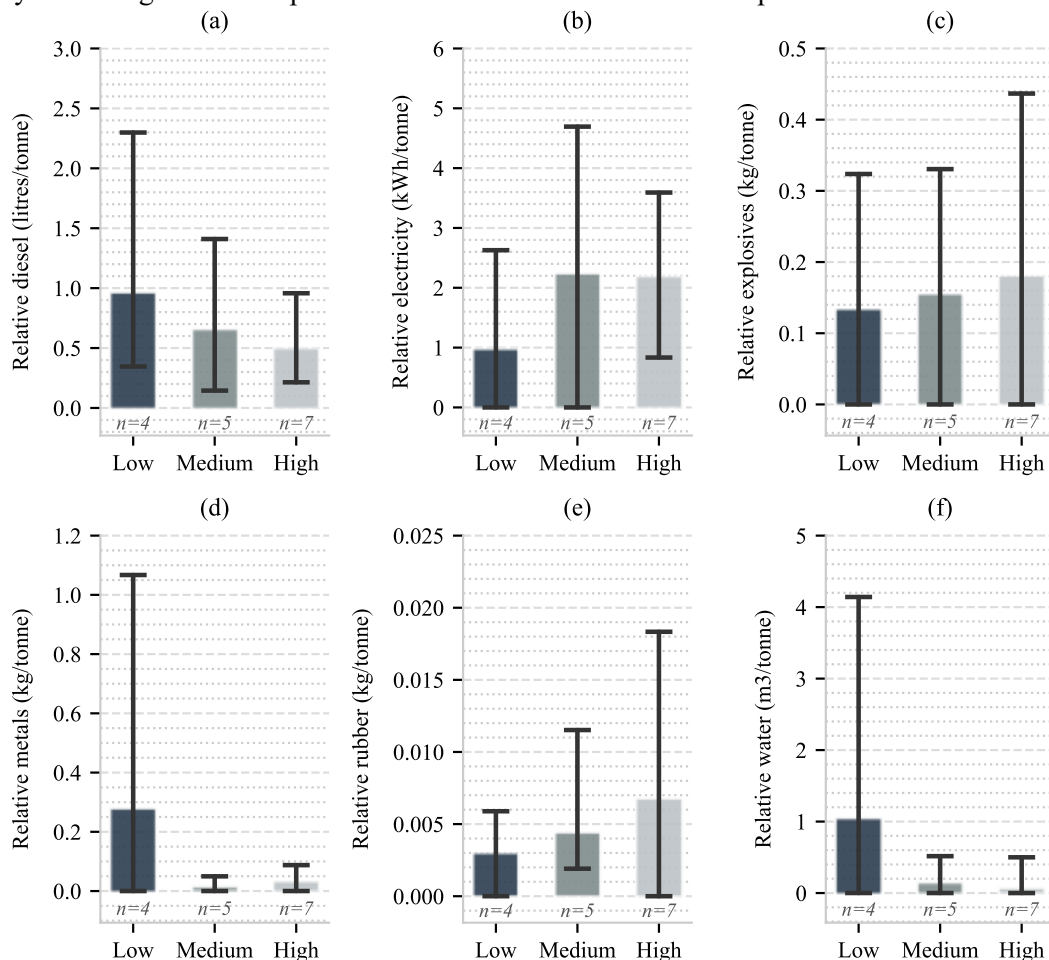


Figure 5: Mean (shown in bars) and range (minimum and maximum, shown as I) of resource consumption per tonne across different production volume categories: (a) diesel, (b) electricity, (c) explosives, (d) metals, (e) rubber, and (f) water.

To investigate the relationship between resource consumption and environmental performance, a contribution analysis was conducted to estimate the proportion of the impacts attributable to diesel, electricity, and explosives consumption across the three production volume categories. Figure 6 shows that the diesel consumption was the primary contributor to GWP-total across all volume categories, accounting for mean contributions of 71%, 55%, and 63% in the low, medium, and high volume categories, respectively. The highest contribution from diesel is observed in the low-volume category, where sites use mobile processing circuits in which diesel is the primary energy source for both material transport and production. In the medium and high volume categories, electricity accounts for 20% and 14% of GWP-total, respectively. This is due to the use of stationary processing circuits that rely on electricity for production and the CO₂ intensity of the grid supplying that electricity. The contribution of explosives to GWP-total remains consistent across all three volume categories, ranging from 11% to 13.1%, as most sites use blasting for extraction irrespective of production volume. It should be noted that there is site-level variation in the contribution from different resources; for instance, in both medium and high volume categories, the electricity contribution ranges from zero to over 50%.

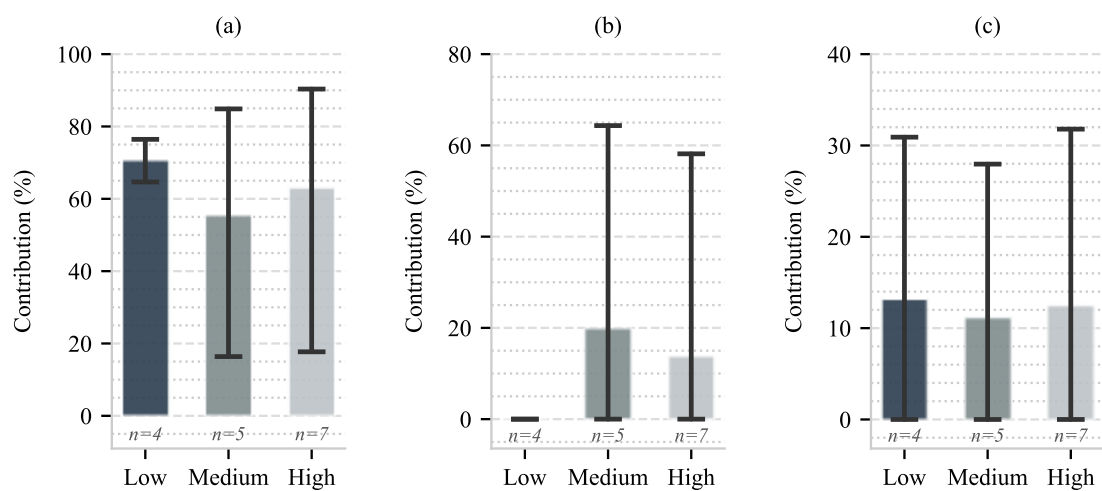


Figure 6: Mean (shown in bars) and range (minimum and maximum, shown as I) of the contribution of different resources to GWP-total: (a) diesel, (b) electricity, and (c) explosives.

4. Remarks and future work

This study presents preliminary findings from a benchmarking study of the environmental performance of 16 quarrying sites. The results demonstrate variation in environmental performance across the 16 sites. The results underscore differences in consumption patterns across production volume categories that influence environmental performance. Furthermore, the observed pattern in environmental performance suggests interconnections between operational and design attributes. For example, high-volume sites mainly use stationary circuits in production, which rely on electricity showed better environmental performance compared with low-volume sites that rely on mobile diesel-powered circuits. In addition, the results also indicate that the environmental performance improves with increasing production volume. On the other hand, future research is necessary to identify the influence of other attributes on the environmental performance.

As future work, further data collection is ongoing to expand the dataset from 16 sites. This will enable the inclusion of more sites per production volume category, and broader geographic coverage would improve the statistical robustness of category-level comparisons. This can lead to more reliable identification of systematic patterns across categories and relationships between site-specific attributes and environmental performance. With additional data, it is possible to investigate the sites using different categorizations, for example, by type of circuit and rock type. This can lead to different perspectives.

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