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Processing Coalmine Overburden Waste Rock as Replacement to Natural Sand: Environmental Sustainability Assessment

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Abstract: Waste rock dumped beside a surface coal mining site is termed coalmine overburden (OB) and is found suitable as a construction material. It requires preprocessing to be converted into the final construction material. The waste rock (cradle) processing to the final product (gate) involves transportation to the processing plant, crushing, screening, washing, and transportation from the processing plant to the client or project site. Preprocessing will cause environmental impacts. The present study performs a cradle-to-gate environmental impact assessment of waste rock to replace natural sand at a coal mine near Dhanbad, India. Life cycle environmental sustainability is assessed using the SimaPro® CML-IA baseline V3.07/EU+3 2000 impact method with the Ecoinvent 3.0 inventory. The data used was collected from an operational plant in the nearby area. The layout of a typical processing plant is also proposed in the study. The environmental impacts are reported in terms of abiotic depletion, global warming potential, ozone depletion potential, terrestrial ecotoxicity, human toxicity, eutrophication, acidification, and eutrophication. The manufacture of overburden sand (OBS) using a sustainable fuel and energy mix is more environmentally friendly. The environmental impacts can be drastically reduced if crushing is carried out using an onsite or mobile crushing plant.

Keywords: coalmine overburden; waste rock; environmental impact; crushed sand; environmental sustainability

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1. Introduction

Silica is the most used mineral by mass in manufacturing and construction and is becoming increasingly scarce. The situation is grave. Growing demand is harming the environment, causing social problems, and raising concerns about sand scarcity [1]. The building sector of the global economy accounts for a significant portion of global energy and raw material/natural resource use. This largely stems from the fact that most industrialized building materials utilized today have substantial environmental effects during production [2]. Coalmine waste rock, generally termed as overburden (OB), is an excellent alternative to natural sand that can collectively resolve the sustainability issues of the building and mining industries if bulk utilization is carried out in construction practices. It is composed chiefly of sandstone, shale, greystone, and soil [3,4]. The waste rock (cradle) processing to the final product (gate) involves transportation to the processing plant, crushing, screening, washing, and transportation from the processing plant to the client or project site. An installation that meets the necessary production requirements; operates at a competitive cost; complies with strict environmental regulations; and is constructible at an affordable price, despite the rising costs of construction materials, energy, and equipment, is the fundamental aim for the design of a crushing plant. The increasing demand for environmentally friendly products and the rise in environmental consciousness worldwide are driving the industry to adopt the "sustainability" paradigm. As a result, the industry is gradually beginning to use materials that have less embodied energy, have fewer adverse effects on the environment, and are more suitable for factors such as the local climate [2]. All this preprocessing will have environmental impacts. Even if the material is suitable for construction, these environmental impacts must be quantified.

Literature covering the environmental impacts of production and processing is available. Life cycle impact assessments of the production of aluminum [5], cement mortar and concrete [6–8], geopolymer concrete [9,10], aggregates production [11], and asphalt pavement aggregate [12] are available. Limited literature on the comparative environmental assessment of recycled aggregate [13], shredded tires [14], and construction and demolition waste [15] is available. Only literature covering OB as a sub-blast in railways [16] is available as per the authors' current knowledge. Around the world, coal is mined for various purposes using either underground or surface mining techniques, depending on the depth of the coal seam. Waste rocks produced by the mining of coal are discarded nearby. Managing these waste rocks is a significant challenge in most coal mining sites.

In most cases, the use of waste rocks and the environmental viability of turning them into aggregates have not been investigated. The present study examines the environmental impacts of processing OB waste rock to replace natural sand. The processing data used is collected from an operational plant in the nearby area. The layout of a typical processing plant is also proposed in the study. The environmental impacts are reported in terms of mid-point indicators such as abiotic depletion (ADP), abiotic depletion fossil fuels (ADP F), global warming potential (GWP), ozone depletion potential (ODP), terrestrial ecotoxicity (TET), human toxicity (HT), freshwater aquatic ecotoxicity (FAET), marine aquatic ecotoxicity (MAET), photochemical oxidation (PCOD), acidification (AP), and eutrophication (EP). A comparison of different scenarios involving the impact of change in fuels and energy sources, change of source and quantity of water to be used, and change of location of a processing unit with the conventional baseline processing technique is studied. The most critical impact categories are identified, and sustainable solutions are recommended to reduce the environmental load.

2. Life Cycle Assessment (LCA)

A boulder and cobble size fraction greater than 600 mm is considered for processing into a sand fraction. The procedure to assess the environmental effects of a process, product, or system across the course of its life cycle is defined by ISO 14040 (2006) [17] and ISO 14044 (2006) [18]. As shown in Figure 1, the LCA methodology framework is divided into the following steps per ISO standards: 1. Goal and scope definition; 2. Inventory analysis; 3. Impact evaluation; and 4. Interpretation.

2.1. Goal and Scope Definition

This phase includes determining the product, process, or system to be examined, creating a valid basis for contrasting the processes or products under evaluation, and selecting the proper level of detail or system boundaries. The aim of the present study is to (1) evaluate the environmental impacts of processing a unit mass of coalmine overburden waste rock (OBR) into overburden sand (OBS) using a conventional crushing process (M1), (2) evaluate the environmental impacts of processing a unit mass of OBR into OBS using renewable energy sources (M2), (3) compare the LCA of M1 and M2, (4) assess the influence of change in source and quantity of water in method M1, and (5) assess the impact of a change in the location of the processing plant. The analysis of the different processes is carried out as per ISO 14040 (2006) [17] and ISO 14044 (2006) [18]. For the analysis, the product's life is considered from cradle to gate.

Cradle to gate LCA: The study examines a product's whole life cycle, from the point at which waste rock is placed onto a dump truck for transport to a processing facility to the point at which the finished product (processed sand) is loaded into a dump truck for delivery to the site. The emissions caused during transportation, crushing, washing, and conveying are considered. Based on a nearby coarse aggregate processing plant, the capacity of the proposed plant is considered to be 150 TPH (tons per hour) and the processing machinery's specifications are based on the material and plant capacity.

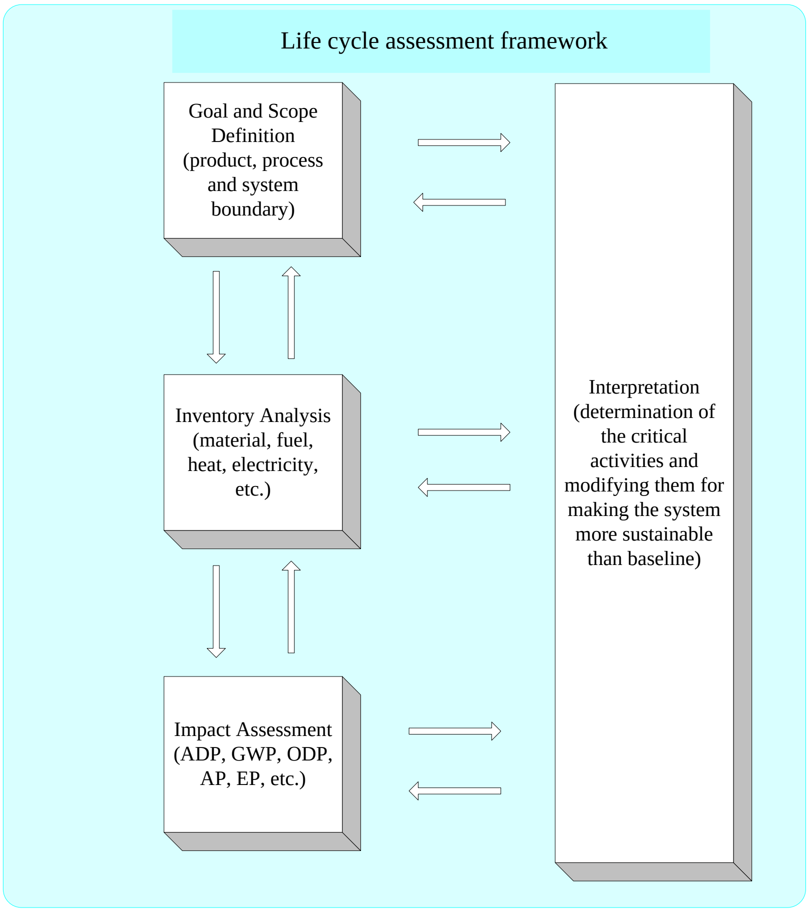

Figure 1. Life cycle assessment framework.

2.1.1. System Boundary

The system boundary for the present study includes transportation of the OBR from the dump site to the processing plant, crushing of the OBR to OBS, conveyancing to the processing subunits, washing of the sand fraction, stocking of the finished product, and loading of the finished product into the lorry for transportation to the site as shown in Figure 2. The acquisition of land for setting up the plant is considered, and groundwater consumption estimated as 2 L per kg of sand washing is assumed for the calculation as input from nature.

2.1.2. Functional Unit

The functional unit in the present study is defined as the processing of 1 ton of OBS from 1 ton of OBR starting from the acquisition of land to the final finished product.

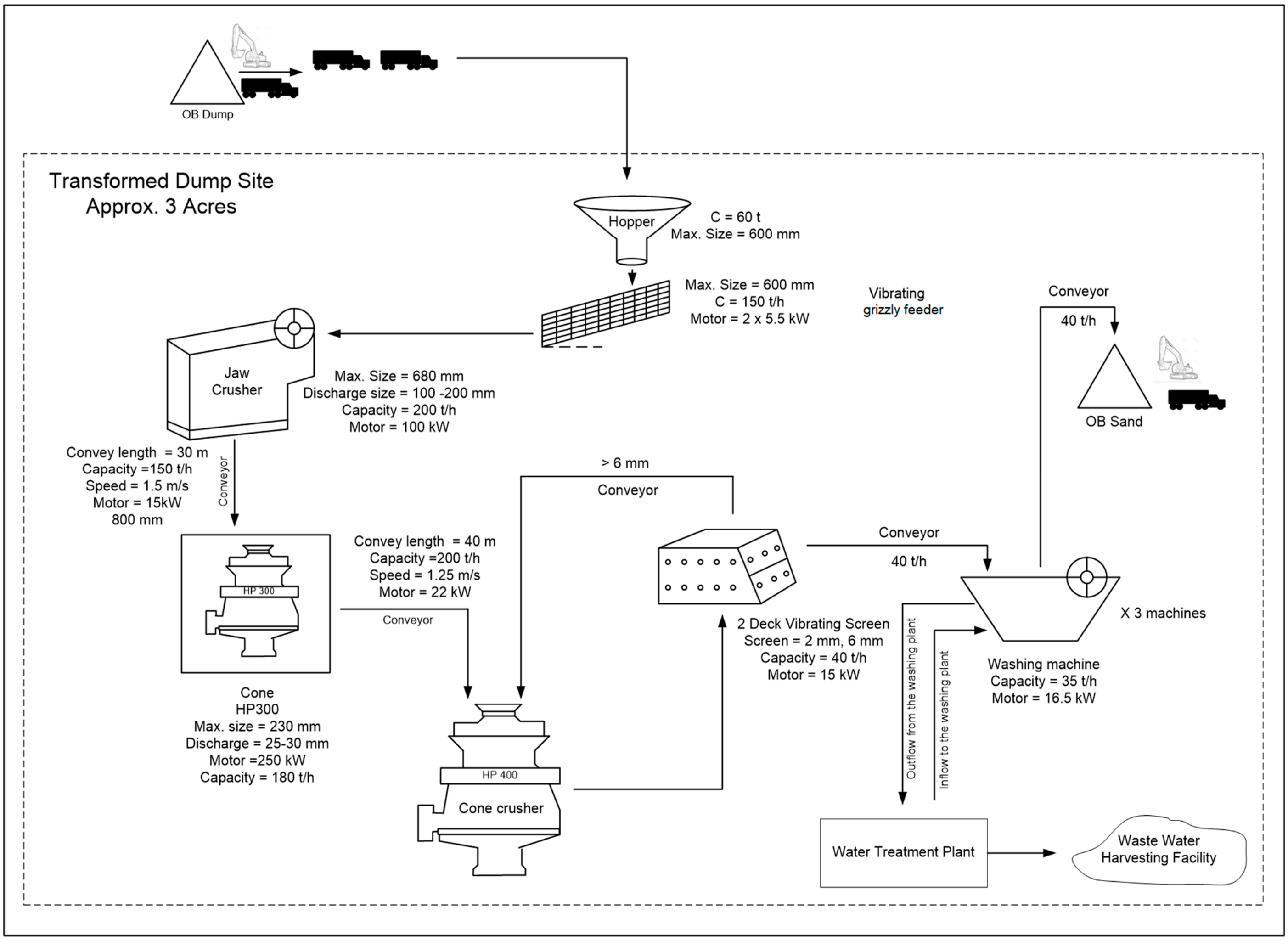

Figure 2. Layout of the proposed processing plant.

2.2. Life Cycle Inventory (LCI)

This phase covers identifying and quantifying the environmental loads caused by the different processes involved in the processing plant. Since OBR is not a well-known building material, the data used in the present study was collected from an operational plant for natural aggregate near the institute campus with some modifications (capacity of sand crusher, sand washing unit, screen size, size of conveyor belt, and related power consumption, for optimal operational efficiency) for operating a similar processing plant for producing OBS. The LCI of transportation, fuel, natural gas, electricity, solar heat, and water consumption were obtained from the Ecoinvent 3.0 database. A land area of 3 acres is considered for setting up a processing plant of 150TPH capacity operating 8 h per day. The distance of the processing unit from the dump site to the processing plant is varied (0.5 km, 5 km, 50 km, and 200 km) to calculate the impact of location distance on environmental indicators. In a similar way, the change in the quantity (2 L, 5 L, and 10 L) and source (nature or the technosphere) of water used to wash the sand are also investigated

OBR obtained from the dumpsite is not considered for impact assessment, regarded as the industrial waste of coal mining industries during coal extraction. The impact evaluation is deemed to begin from transforming dumpsite land to setting up the processing plant. The life cycle of OBR involves loading the dump truck using poclain at a diesel consumption rate of 9 L/h (liters per hour), and the density of diesel is considered as 0.85 g/cc. The dump truck transporting the OBR to the processing plant consumes diesel at 2 L/h. The installed grizzly feeder, cone crusher, conveyor, vibrating screen and washing plant, and the number of units are selected in line with the plant's capabilities of 150 TPH. The input feed size, discharge size, capacity, and motor power of each equipment are obtained from the JXCE mine machinery factory database available on the company's website [19]. The complete processing under the system boundary is modelled and analyzed using the commercially available software package SimaPro 9®. SimaPro is a sustainability assessment tool created by the Dutch business PRé Sustainability to model and examine the environmental effects of various processes, goods, and systems based on ISO 14040. SimaPro's accessibility to numerous databases and impact assessment techniques facilitates simple modelling and produces incredibly transparent findings [16].

2.3. Life Cycle Impact Assessment (LCIA)

This phase quantifies the potential environmental impacts due to the quantified environmental load in the LCI phase of the product or process [20]. The LCIA of 1 ton of OBS produced from processing OBR is considered in the present study. In this stage, the environmental damage caused by each inventory process is linked. The database used is the Ecoinvent 3.0 database, and the method of impact assessment is CML-IA baseline/ EU3+ 2000. Several effect categories and characterization techniques for the impact assessment stage were proposed in 2001 by a team of scientists working under the direction of the CML (Center of Environmental Science of Leiden University). The CML-IA impact assessment approach is described as the midpoint strategy. If there are many options for compulsory impact categories, the baseline indicator is chosen using the best practice standard. These "baseline indicators" (problem-oriented approach) are category indicators at the "mid-point" level [21]. This method includes 11 mid-point impact categories that include ADP (kg Sb eq.), ADP_F (MJ), GWP (kg CO_2 eq), ODP (kg CFC -11 eq), HT (kg 1,4-DB eq), FAET (kg 1,4-DB eq), MAET (kg 1,4-DB eq), TET (kg 1,4-DB eq), PCOD (kg C_2H_4 eq), AP (kg SO_2 eq), and EP (kg $PO_4{}^{-3}$ eq).

3. Results

According to the CML-IA baseline technique, the results for several midpoint indicators for process M1, process M2, comparison of M1 and M2, the impact of change in source and quantity of water source, and the impact of changes in the location of the plant are discussed in this section.

3.1. Scenario Analysis

3.1.1. Environmental Impacts Due to Processing OBR to OBS Using M1

The processing of 1 ton OBR to 1 ton OBS through M1 contributes 8.30×10^{-7} kg Sb eq. of ADP, 86.13 MJ of ADP_F, 5.81 kg CO_2 eq of GWP, 8.58×10^{-8} kg CFC-11 eq of ODP, 1.48 kg 1,4-DB eq of HT, 1.32 kg 1,4-DB eq of FAET, 8192.33 kg 1,4-DB eq of MAET, 0.00375 kg 1,4-DB eq of TET, 0.0014 kg C_2H_4 eq of PCOD, 0.0399 kg SO_2 eq of AP, and 0.0093 kg $PO_4{}^{-3}$ eq of EP as shown in Table 1. The percentage contribution of the different subprocesses is shown in Figure 3. The crushing of OBR to OBS is the most critical process contributing 68% and 66% of ADP and ADP_F, respectively, due to the extraction of mineral and fossil fuels for the electricity requirement of the crushers. It contributes 72% of the total for HT, FAET, MAET, TET, and EP, each due to the emission of toxic substances during electricity production into the human environment, freshwater ecosystems, marine ecosystems, and terrestrial ecosystems, and the release of macronutrients in the environment. It also contributes 71% of the GWP and PCOD, respectively, due to the emission of greenhouse gases and the formation of reactive substances harmful to human health and the ecosystem. However, the emissions caused by the process M1 are 0.75% in ADP, 2.36% in ADP_F, 1.5% in AP, 3.8% in EP, 1.8% in GWP, and 0.98% in PCOD impact categories compared to that of processing zircon sand [22]. Compared to silica sand beneficiation by simulation, the emission caused by M1 is 17.6% in GWP, 1.84% in ODP, and 0.41% in PCOD impact categories [23]. It is important to note that the ReCiPe model is used to evaluate the emission in silica sand beneficiation.

Table 1. Environmental impacts due to process M1.

Impact Category	ADP	ADP_F	GWP	ODP	HT	FAET	MAET	TET	PCOD	AP	EP
Unit	**kg Sb eq**	**MJ**	**kg CO_2 eq**	**kg CFC-11 eq**	**kg 1,4-DB eq**	**kg 1,4-DB eq**	**kg 1,4-DB eq**	**kg 1,4-DB eq**	**kg C_2H_4 eq**	**kg SO_2 eq**	**kg PO_4—eq**
Total	8.31×10^{-7}	$8.61 \times 10^{+01}$	5.81	8.58×10^{-8}	1.48	1.32	$8.19 \times 10^{+03}$	3.74×10^{-3}	1.48×10^{-3}	4.00×10^{-2}	9.37×10^{-3}
Coalmine overburden waste rock sand_M1	0	0	0	0	6.83×10^{-3}	0	0	0	0	0	0
Overburden dump waste rock	0	0	0	0	0	0	0	0	0	0	0
Diesel, low sulfur {RoW} | market for Dump truck _to site | Alloc Def, U	1.97×10^{-8}	2.11	2.59×10^{-2}	9.94×10^{-9}	3.50×10^{-3}	1.60×10^{-3}	7.59	9.16×10^{-6}	1.20×10^{-5}	1.74×10^{-4}	1.92×10^{-5}
Diesel {RoW} | market for Poclain | Alloc Def, U	1.64×10^{-8}	2.77	3.16×10^{-2}	1.31×10^{-8}	3.92×10^{-3}	1.61×10^{-3}	7.90	9.73×10^{-6}	1.50×10^{-5}	2.09×10^{-4}	2.16×10^{-5}
Diesel {RoW} | market for Payloader | Alloc Def, U	1.67×10^{-8}	2.82	3.21×10^{-2}	1.33×10^{-8}	3.98×10^{-3}	1.64×10^{-3}	8.03	9.88×10^{-6}	1.52×10^{-5}	2.12×10^{-4}	2.19×10^{-5}
vibrating grizzly feeder (electricity)	1.42×10^{-8}	1.43	1.04×10^{-1}	9.01×10^{-10}	2.67×10^{-2}	2.40×10^{-2}	$1.49 \times 10^{+02}$	6.76×10^{-5}	2.63×10^{-5}	7.18×10^{-4}	1.70×10^{-4}
Jaw Crusher (electricity)	1.29×10^{-7}	$1.30 \times 10^{+01}$	9.48×10^{-1}	8.19×10^{-9}	2.43×10^{-1}	2.18×10^{-1}	$1.35 \times 10^{+03}$	6.14×10^{-4}	2.39×10^{-4}	6.53×10^{-3}	1.54×10^{-3}
Conveyor 800 mm (electricity)	1.93×10^{-8}	1.95	1.42×10^{-1}	1.23×10^{-9}	3.64×10^{-2}	3.27×10^{-2}	$2.03 \times 10^{+02}$	9.21×10^{-5}	3.58×10^{-5}	9.79×10^{-4}	2.31×10^{-4}
HP Cone Crusher 300 (electricity)	3.22×10^{-7}	$3.25 \times 10^{+01}$	2.37	2.05×10^{-8}	6.07×10^{-1}	5.45×10^{-1}	$3.38 \times 10^{+03}$	1.54×10^{-3}	5.97×10^{-4}	1.63×10^{-2}	3.85×10^{-3}
Conveyor 400 mm (electricity)	2.84×10^{-8}	2.86	2.09×10^{-1}	1.80×10^{-9}	5.34×10^{-2}	4.80×10^{-2}	$2.98 \times 10^{+02}$	1.35×10^{-4}	5.25×10^{-5}	1.44×10^{-3}	3.39×10^{-4}
HP Cone Crusher 300_30_2 (electricity)	1.13×10^{-7}	$1.14 \times 10^{+01}$	8.30×10^{-1}	7.17×10^{-9}	2.12×10^{-1}	1.91×10^{-1}	$1.18 \times 10^{+03}$	5.37×10^{-4}	2.09×10^{-4}	5.71×10^{-3}	1.35×10^{-3}
2 Deck Vibrating Screen (electricity)	1.93×10^{-8}	1.95	1.42×10^{-1}	1.23×10^{-9}	3.64×10^{-2}	3.27×10^{-2}	$2.03 \times 10^{+02}$	9.21×10^{-5}	3.58×10^{-5}	9.79×10^{-4}	2.31×10^{-4}
Conveyor 400 mm deck to cone HP 300 (electricity)	2.84×10^{-8}	2.86	2.09×10^{-1}	1.80×10^{-9}	5.34×10^{-2}	4.80×10^{-2}	$2.98 \times 10^{+02}$	1.35×10^{-4}	5.25×10^{-5}	1.44×10^{-3}	3.39×10^{-4}
Conveyor 400 mm Deck to Washing Plant(electricity)	1.93×10^{-8}	1.95	1.42×10^{-1}	1.23×10^{-9}	3.64×10^{-2}	3.27×10^{-2}	$2.03 \times 10^{+02}$	9.21×10^{-5}	3.58×10^{-5}	9.79×10^{-4}	2.31×10^{-4}
Washing Plant x 3U 40TPH(electricity)	4.25×10^{-8}	4.29	3.13×10^{-1}	2.70×10^{-9}	8.01×10^{-2}	7.20×10^{-2}	$4.47 \times 10^{+02}$	2.03×10^{-4}	7.88×10^{-5}	2.15×10^{-3}	5.09×10^{-4}
Conveyor 400 mm x 3_WP_OBSTOCK (electricity)	4.25×10^{-8}	4.29	3.13×10^{-1}	2.70×10^{-9}	8.01×10^{-2}	7.20×10^{-2}	$4.47 \times 10^{+02}$	2.03×10^{-4}	7.88×10^{-5}	2.15×10^{-3}	5.09×10^{-4}
Wastewater treatment, other emissions	0	0	0	0	0	0	0	0	0	0	0

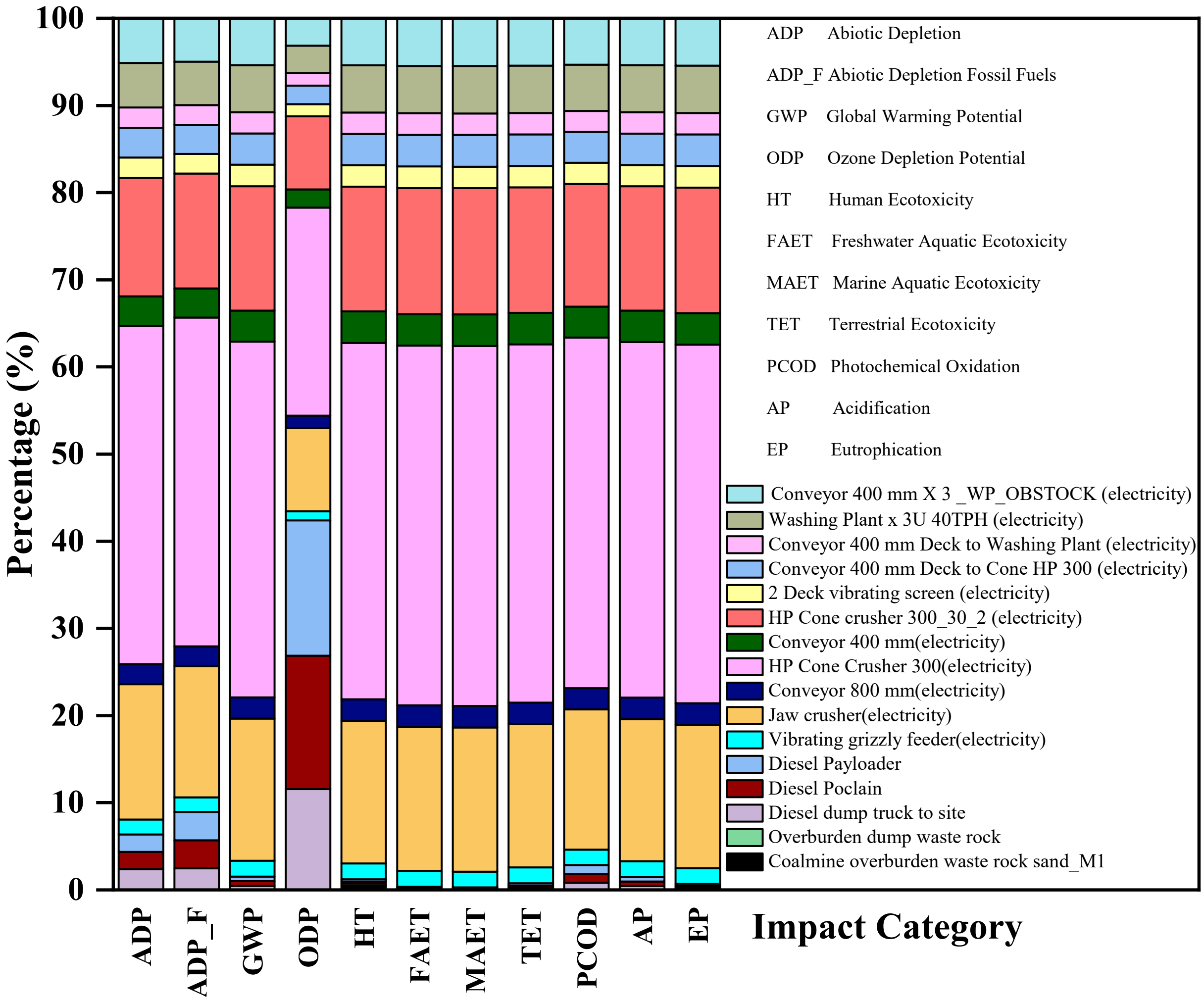

Figure 3. Environmental impact due to individual subprocesses in M1.

3.1.2. Environmental Impacts Due to Processing OBR to OBS Using M2

The processing of 1 ton OBR to 1 ton OBS through M2 contributes 4.36×10^{-6} kg Sb eq. of ADP, 2.59 MJ of ADP_F, 0.259 kg CO_2 eq of GWP, 1.36×10^{-8} kg CFC-11 eq of ODP, 0.39 kg 1,4-DB eq of HT, 0.21 kg 1,4-DB eq of FAET, 890.43 kg 1,4-DB eq of MAET, 0.0060 kg 1,4-DB eq of TET, 0.00012 kg C_2H_4 eq of PCOD, 0.0023 kg SO_2 eq of AP, and 0.000903 kg $PO_4{}^{-3}$ eq of EP as shown in Table 2. The percentage contributions of the different sub-processes are shown in Figure 4. Similar to M1, crushing is the most critical subprocess contributing the maximum fraction of the environmental impact at an almost similar percentage. This may be due to the significant portion of input energy consumed in the crushing process. The GWP and PCOD impact categories are reduced by 18% and 17%; there is a 4% increase in each of the ADP and ADP_F categories. The other indicators are impacted to the same extent as in the case of M1. However, the emission caused by the process M2 is 3.96% in ADP, 0.06 % in ADP_F, 0.09 % in AP, 0.37 % in EP, and 0.08 % in both GWP and PCOD impact categories compared to that of processing zircon sand [22]. Compared to silica sand beneficiation by simulation, the emission caused by M2 is 0.78 % in GWP, 0.29% in ODP, and 0.03% in PCOD impact categories [23].

Table 2. Environmental impacts due to process M2.

Impact Category	ADP	ADP_F	GWP	ODP	HT	FAET	MAET	TET	PCOD	AP	EP
Unit	**kg Sb eq**	**MJ**	**kg CO_2 eq**	**kg CFC-11 eq**	**kg 1,4-DB eq**	**kg 1,4-DB eq**	**kg 1,4-DB eq**	**kg 1,4-DB eq**	**kg C_2H_4 eq**	**kg SO_2 eq**	**kg PO_4—eq**
Total	4.4×10^{-6}	2.6	2.6×10^{-1}	1.4×10^{-8}	4.0×10^{-1}	2.2×10^{-1}	$8.9 \times 10^{+02}$	6.1×10^{-4}	1.2×10^{-4}	2.3×10^{-3}	9.1×10^{-4}
Coalmine overburden waste rock sand_M2	0	0	0	0	0	0	0	0	0	0	0
Overburden dump waste rock	0	0	0	0	0	0	0	0	0	0	0
Dump truck Natural gas_ Dump_to_plant	1.1×10^{-8}	0.0	1.8×10^{-2}	7.8×10^{-12}	1.6×10^{-4}	3.2×10^{-5}	1.7×10^{-1}	7.8×10^{-7}	8.8×10^{-6}	5.9×10^{-5}	1.2×10^{-5}
Poclain Natural gas_ Loading_dumptruck	1.5×10^{-8}	0.0	2.5×10^{-2}	1.0×10^{-11}	2.1×10^{-4}	4.3×10^{-5}	2.3×10^{-1}	1.0×10^{-6}	1.2×10^{-5}	7.8×10^{-5}	1.5×10^{-5}
Payloader Natural gas_ Loading_sand_truck	1.5×10^{-8}	0.0	2.5×10^{-2}	1.1×10^{-11}	2.2×10^{-4}	4.4×10^{-5}	2.3×10^{-1}	1.1×10^{-6}	1.2×10^{-5}	7.9×10^{-5}	1.6×10^{-5}
Vibrating grizzly solar energy	7.9×10^{-8}	4.7×10^{-2}	3.5×10^{-3}	2.5×10^{-10}	7.2×10^{-3}	4.0×10^{-3}	$1.6 \times 10^{+01}$	1.1×10^{-5}	1.6×10^{-6}	3.9×10^{-5}	1.6×10^{-5}
Jaw crusher solar energy	7.2×10^{-7}	4.3×10^{-1}	3.2×10^{-2}	2.3×10^{-9}	6.5×10^{-2}	3.6×10^{-2}	$1.5 \times 10^{+02}$	1.0×10^{-4}	1.5×10^{-5}	3.5×10^{-4}	1.4×10^{-4}
Conveyor_800_ _solar energy	1.1×10^{-7}	6.5×10^{-2}	4.8×10^{-3}	3.4×10^{-10}	9.8×10^{-3}	5.4×10^{-3}	$2.2 \times 10^{+01}$	1.5×10^{-5}	2.2×10^{-6}	5.3×10^{-5}	2.1×10^{-5}
HP_Cone_crusher_ 300_solar energy	1.8×10^{-6}	1.1	8.0×10^{-2}	5.6×10^{-9}	1.6×10^{-1}	9.1×10^{-2}	$3.7 \times 10^{+02}$	2.5×10^{-4}	3.7×10^{-5}	8.8×10^{-4}	3.6×10^{-4}
Conveyor_400__ solar energy	1.6×10^{-7}	9.5×10^{-2}	7.0×10^{-3}	5.0×10^{-10}	1.4×10^{-2}	8.0×10^{-3}	$3.2 \times 10^{+01}$	2.2×10^{-5}	3.3×10^{-6}	7.7×10^{-5}	3.2×10^{-5}
HP_Cone_crusher_ 30mm_2mm_solar energy	6.3×10^{-7}	3.8×10^{-1}	2.8×10^{-2}	2.0×10^{-9}	5.7×10^{-2}	3.2×10^{-2}	$1.3 \times 10^{+02}$	8.8×10^{-5}	1.3×10^{-5}	3.1×10^{-4}	1.3×10^{-4}
2_Deck_vibrating Screen _6mm_2mm__solar energy	1.1×10^{-7}	6.5×10^{-2}	4.8×10^{-3}	3.4×10^{-10}	9.8×10^{-3}	5.4×10^{-3}	$2.2 \times 10^{+01}$	1.5×10^{-5}	2.2×10^{-6}	5.3×10^{-5}	2.1×10^{-5}
Conveyor_400_Deck_ HP_Cone_solar energy	1.6×10^{-7}	9.5×10^{-2}	7.0×10^{-3}	5.0×10^{-10}	1.4×10^{-2}	8.0×10^{-3}	$3.2 \times 10^{+01}$	2.2×10^{-5}	3.3×10^{-6}	7.7×10^{-5}	3.2×10^{-5}
Conveyor_400_Deck_to_ Washing_plant__solar energy	1.1×10^{-7}	6.5×10^{-2}	4.8×10^{-3}	3.4×10^{-10}	9.8×10^{-3}	5.4×10^{-3}	$2.2 \times 10^{+01}$	1.5×10^{-5}	2.2×10^{-6}	5.3×10^{-5}	2.1×10^{-5}
Washing plant_ _solar energy	2.4×10^{-7}	1.4×10^{-1}	1.0×10^{-2}	7.5×10^{-10}	2.2×10^{-2}	1.2×10^{-2}	$4.9 \times 10^{+01}$	3.3×10^{-5}	4.9×10^{-6}	1.2×10^{-4}	4.7×10^{-5}
Conveyor_400_washingplan t_to_OBstockpile_solar energy	2.4×10^{-7}	1.4×10^{-1}	1.0×10^{-2}	7.5×10^{-10}	2.2×10^{-2}	1.2×10^{-2}	$4.9 \times 10^{+01}$	3.3×10^{-5}	4.9×10^{-6}	1.2×10^{-4}	4.7×10^{-5}

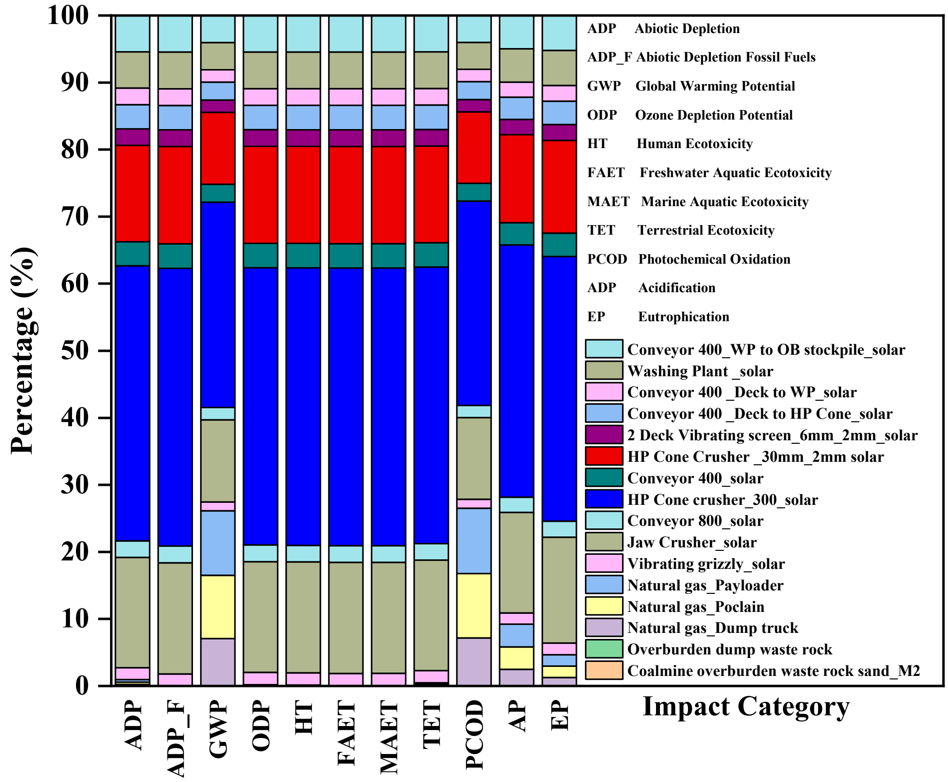

Figure 4. Environmental impacts due to individual subprocesses in M2.

For the contribution of different subprocesses in the midpoint impact categories, refer to the Supplementary Material provided.

3.1.3. Comparison of M1 and M2

The comparative analysis of the conventional process (M1) and the replacement sustainable process (M2) is shown in Table 3. The processing of OBR to OBS through M2 reduced the ADP_F to 3%, GWP to 4%, ODP to 17%, HT to 27%, FAET to 17%, MAET to 11%, TET to 16%, PCOD to 8%, AP to 6%, and EP to 10% in comparison to M1. Although the ADP increased by 81%, considering the contribution of M1 as 100%, this may be due to natural gas processing requiring the extraction of minerals. The percentage contribution of the different subprocesses in M1 and M2 is shown in Figure 5. The replacement of diesel with natural gas and coal-powered electricity with solar power reduced emissions to a large extent.

Table 3. Comparative environmental impacts of methods M1 and M2.

Impact Category	ADP	ADP_F	GWP	ODP	HT	FAET	MAET	TET	PCOD	AP	EP
Unit	kg Sb eq	MJ	kg CO_2 eq	kg CFC-11 eq	kg 1,4-DB eq	kg 1,4-DB eq	kg 1,4-DB eq	kg 1,4-DB eq	kg C_2H_4 eq	kg SO_2 eq	kg PO_4—eq
Coalmine overburden waste rock sand_M1	8.18×10^{-7}	$8.47 \times 10^{+01}$	5.80	7.92×10^{-8}	1.48	1.32	$8.19 \times 10^{+03}$	3.73×10^{-3}	1.48×10^{-3}	3.99×10^{-2}	9.36×10^{-3}
Coalmine overburden waste rock sand_M2	4.35×10^{-6}	2.60	2.48×10^{-1}	1.36×10^{-8}	3.95×10^{-1}	2.19×10^{-1}	$8.90 \times 10^{+02}$	6.08×10^{-4}	1.17×10^{-4}	2.30×10^{-3}	8.99×10^{-4}

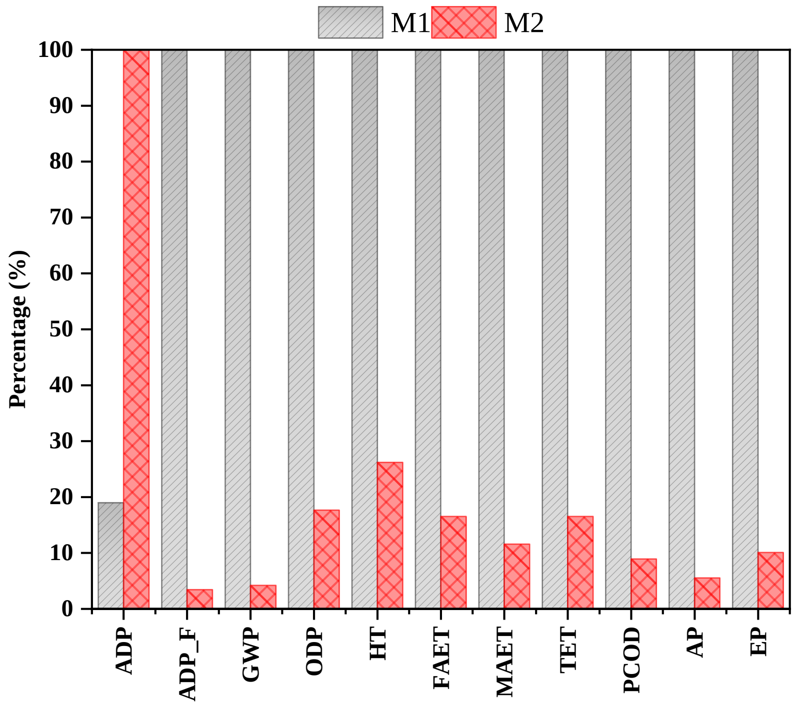

Figure 5. Comparative environmental impacts caused by M1 and M2 in percent.

3.1.4. Impact of Change of Source and Quantity of Water

The impact of the change of water source to be used for washing the processed OBS is studied by changing the source from groundwater to lake water as input from nature, and then to tap water from the technosphere for the industrial process, as shown in Table 4. It is observed that there is no change in the indicators when the source changes from groundwater to lake water; this may be due to both the inputs being from nature so that they contribute equally to the indicators. However, when the source was changed from groundwater to tap water, it was observed that the ADP increased by 70%, ADP_F increased by 12%, GWP increased by 14%, ODP increased by 27%, HT increased by 17%, FAET increased by 23%, MAET increased by 12%, TET increased by 19%, PCOD increased by 15%, AP increased by 14%, and EP increased by 13%, considering 2 L of water per kg of sand washing using the process M1 as the baseline. The increase in the indicators may be collectively attributed to the emissions caused by processing and supplying tap water to the site.

Table 4. Comparative environmental impacts due to change in the source of water.

Impact Category	ADP	ADP_F	GWP	ODP	HT	FAET	MAET	TET	PCOD	AP	EP
Unit	**kg Sb eq**	**MJ**	**kg CO_2 eq**	**kg CFC-11 eq**	**kg 1,4-DB eq**	**kg 1,4-DB eq**	**kg 1,4-DB eq**	**kg 1,4-DB eq**	**kg C_2H_4 eq**	**kg SO_2 eq**	**kg PO_4—eq**
Coalmine overburden waste rock sand_M1_2L	8.31×10^{-7}	$8.61 \times 10^{+01}$	5.81	8.58×10^{-8}	1.48	1.32	$8.19 \times 10^{+03}$	3.74×10^{-3}	1.48×10^{-3}	4.00×10^{-2}	9.37×10^{-3}
Coalmine overburden waste rock sand_M1_2L_lake	8.31×10^{-7}	$8.61 \times 10^{+01}$	5.81	8.58×10^{-8}	1.48	1.32	$8.19 \times 10^{+03}$	3.74×10^{-3}	1.48×10^{-3}	4.00×10^{-2}	9.37×10^{-3}
Coalmine overburden waste rock sand_M1_2L_ watertransformation	2.79×10^{-6}	$9.82 \times 10^{+01}$	6.76	1.17×10^{-7}	1.78	1.71	$9.32 \times 10^{+03}$	4.62×10^{-3}	1.75×10^{-3}	4.63×10^{-2}	1.08×10^{-2}
Coalmine overburden waste rock sand_M1_5L_ watertransformation	5.73×10^{-6}	$1.16 \times 10^{+02}$	8.18	1.64×10^{-7}	2.22	2.28	$1.10 \times 10^{+04}$	5.95×10^{-3}	2.15×10^{-3}	5.57×10^{-2}	1.28×10^{-2}
Coalmine overburden waste rock sand_M1_10L_ watertransformation	1.06×10^{-5}	$1.47 \times 10^{+02}$	$1.06 \times 10^{+01}$	2.41×10^{-7}	2.95	3.25	$1.38 \times 10^{+04}$	8.16×10^{-3}	2.81×10^{-3}	7.15×10^{-2}	1.63×10^{-2}

The per liter increase in tap water quantity is found to increase the ADP by 1.2×10^{-6} kg Sb eq, ADP_F by 2.9 MJ, GWP by 2 kg CO_2 eq, ODP by 3.8×10^{-8} kg CFC-11 eq, HT by 5.4×10^{-1} kg 1,4-DB eq, FAET by 5.4×10^{-1} kg 1,4-DB eq, MAET by $2.7 \times 10^{+3}$ kg 1,4-DB eq, TET by 1.4×10^{-3} kg 1,4-DB eq, PCOD by 5.3×10^{-4} kg C_2H_4 eq, AP by 1.4×10^{-2} kg SO_2 eq, and EP by 3.2×10^{-3} kg $PO_4{}^{-3}$ eq. The percentage contribution of each case is shown in Figure 6. These increases may be due to the reason stated above.

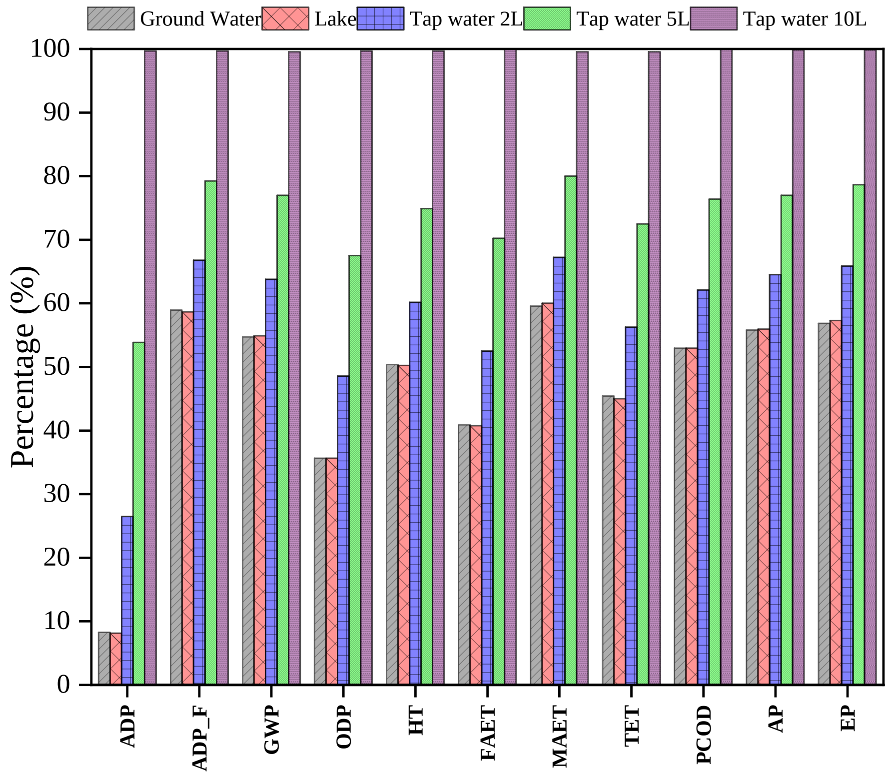

Figure 6. Environmental impacts due to change in source and quantity of water for washing OBS.

3.1.5. Impact of Change in Location of the Processing Plant

The impact of a change in the location of the processing plant is studied by considering the minimum distance of haulage from the dump to be 0.5 km, 5 km, 50 km, and 200 km. It was assumed that an already operational crushing plant exists 5 km, 50 km, and 200 km from the dump site. The percentage contribution of each case is shown in Figure 7, and the absolute contribution is tabulated in Table 5. It is observed that ADP and ADP_F increased by 2%, ODP increased by 9%, and POF increased by 1%. There was an insignificant impact on GWP, HT, FAET, MAET, TET, AP, and EP when the distance was assumed to be 5 km compared to 0.5 km (baseline). When the distance was considered to be 50 km, ADP and ADP_F increased by 14%, ODP increased by 64%, GWP and AP increased by 3%, POF increased by 5%, and HT, FAET, MAET, and TET increased by 1% in comparison to the baseline. In the case of the 200 km assumed location, it is found that ADP and ADP_F increased by approximately 60%, GWP increased by 12%, ODP increased by 195%, PCOD increased by 22%, and AP increased by 12%. HT and TET increased by 7%, EP increased by 6%;, and FAET and MAET increased by 3% compared to the baseline. The increase in the indicators is considered to be due to the emissions caused by diesel-burning in the dump truck for conveying the OBR to the processing unit.

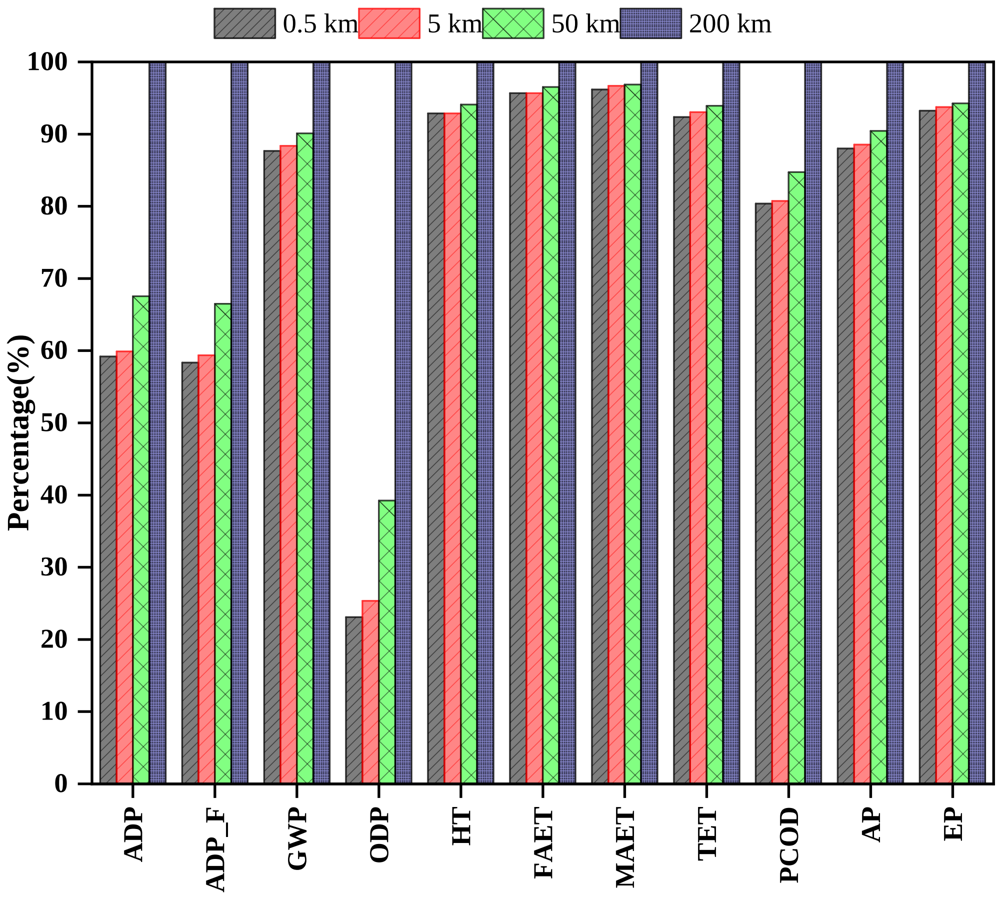

Figure 7. Environmental impacts due to change in location of the processing unit.

Table 5. Comparative environmental impacts due to change in location of the processing plant.

Impact category	ADP	ADP_F	GWP	ODP	HT	FAET	MAET	TET	PCOD	AP	EP
Unit	**kg Sb eq**	**MJ**	**kg CO_2 eq**	**kg CFC-11 eq**	**kg 1,4-DB eq**	**kg 1,4-DB eq**	**kg 1,4-DB eq**	**kg 1,4-DB eq**	**kg C_2H_4 eq**	**kg SO_2 eq**	**kg PO_4— eq**
Coalmine overburden waste rock sand_M1_2L_0.5km	8.31×10^{-7}	$8.61 \times 10^{+01}$	5.81	8.58×10^{-8}	1.48	1.32	$8.19 \times 10^{+03}$	3.74×10^{-3}	1.48×10^{-3}	4.00×10^{-2}	9.37×10^{-3}
Coalmine overburden waste rock sand_M1_2L_5km	8.46×10^{-7}	$8.77 \times 10^{+01}$	5.83	9.33×10^{-8}	1.49	1.32	$8.20 \times 10^{+03}$	3.74×10^{-3}	1.49×10^{-3}	4.01×10^{-2}	9.38×10^{-3}
Coalmine overburden waste rock sand_M1_2L_50km	9.49×10^{-7}	$9.88 \times 10^{+01}$	5.97	1.45×10^{-7}	1.50	1.33	$8.24 \times 10^{+03}$	3.79×10^{-3}	1.56×10^{-3}	4.10×10^{-2}	9.48×10^{-3}
Coalmine overburden waste rock sand_M1_2L_200km	1.39×10^{-6}	$1.46 \times 10^{+02}$	6.55	3.70×10^{-7}	1.58	1.37	$8.41 \times 10^{+03}$	4.00×10^{-3}	1.83×10^{-3}	4.50×10^{-2}	9.92×10^{-3}

4. Conclusions

Based on the analysis of different scenarios using the Ecoinvent 3.0 database as the LCI and CML_IA baseline for the impact assessment method, the following conclusions may be drawn:

1. M2 processing of OBR to OBS compared to M1 is more environmentally sustainable in all impact categories other than ADP, which increased by 81%. Natural gas-operated engines is used for loading and hauling. Solar energy is used to operate the processing equipment in place of conventional coal-powered electricity.
2. The use of tap water for industrial purposes increases the environmental load due to the processing and transfer of water to the site. This can be improved by recycling water at the site by installing a wastewater treatment plant, but the treatment plant's

life cycle assessment also needs to be studied. A better-optimized use of water is required to control the environmental load due to water consumption.

3. The change of location within a 5 km radius of the dump does not significantly contribute to the environmental load. Transportation is the major contributing factor in the processing of OBR to OBS. This can be resolved by developing a mobile crushing unit to produce application-specific gradation wherever possible, whether at the dump or the site of the application of OBS.
4. The outcomes show that OBR processing as an alternative to natural sand can be accomplished sustainably, ending several mining-related problem activities. Additionally, this will create employment opportunities for the local population, with a beneficial impact on society.
5. Current material specifications and standards do not encompass OB as an aggregate. Hence, the future efforts of researchers and policymakers should be directed towards this issue.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su142214853/s1.

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