International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 16s,2025
https://theaspd.com/index.php

Comparative Assessment Of Productivity And Greenhouse Gas Emissions In Mechanized Vs. Manual Beach Sand Mining And Sand Drying Methods

Nithiya Kalyani, K[1,2]*, Patterson Edward, J.K[1]
[1]*Suganthi Devadason Marine Research Institute, 44-Beach Road, Tuticorin 628 001, India*
[2]Registration No:17217022052002, Manonmaniam Sundaranar University
Manonmaniam Sundaranar University, Abishekapatti, Tirunelveli – 627012. Tamil Nadu, India)
*Corresponding author: Email: k.nithiyakalyani@gmail.com

Abstract
The present study provides a comparative assessment of greenhouse gas (GHG) emissions and productivity between conventional (mechanized) and green mining (manual and solar-powered) methods of beach sand mining and drying in southern India. Three front-end loaders – JCB 433-4, Caterpillar 966H and JCB 407 were examined for their fuel consumption, productivity and associated GHGs emissions. Similarly, the productivity and GHGs emissions from the manual mining and solar drying methods were examined. The findings indicate that Caterpillar 966H had the highest productivity (262.07 tons/hr) but with a higher emission intensity of 0.158 kg CO_{2e}/ton, whereas JCB 433-4 demonstrated greater fuel efficiency with the lowest GHG emission intensity of 0.064 kgCO_{2e}/ton. On the other hand manual mining although having lower productivity (25 tons/hr), resulted in no direct emission of GHGs, highlighting its environmental advantages. In the sand drying methods, rotary dryer used 180 liters of diesel per hour to achieve a drying capacity of 15 tons/hr, resulting in a significant carbon footprint of 32.336 kg CO_{2e}/ton. On the other hand, solar drying, utilizing 5.8 kW/m^2 of solar irradiance, effectively dried beach sand without fuel consumption or GHG emissions, although its performance was influenced by space and climate conditions. The study underscores that while mechanized methods (conventional) of mining and drying beach sand were superior in productivity, they contribute significantly to GHG emissions. Manual mining and solar drying (green mining) may be less productive but provide zero-emission options that could be vital in promoting sustainable beach mineral sand management and strategies to mitigate climate change implications and also to offset carbon in India's Nationally Determined Contribution.
Key words: *Conventional mining, Green technology, rotary-dryer, solar drying, beach mineral sand*

1. INTRODUCTION

Global warming is responsible for climate change effects worldwide and is recognized as a significant human-induced global environmental challenge (Yang et al., 2008). This increase in temperature is cumulative and irreversible on time-scale of centuries (Solomon et al., 2008). The urgent global need to mitigate climate change effects has resulted in an increased emphasis on sustainable resource extraction and development of green technologies (Ting & Hagh, 2023). Although energy generation and industrial emissions are major contributions to greenhouse gas (GHG) concentrations, the extractive sector—particularly mineral mining—can significantly contribute to climate mitigation through the adoption of sustainable practices and carbon management strategies (IPCC, 2021). Global mining sector is responsible for 4-7% of greenhouse gas emissions.

'Green mining' seeks to minimize the ecological consequences of mining through more efficient technologies and reducing waste. This method focuses on utilizing renewable energy sources, promoting recycling, and creating innovative strategies to lessen the environmental effects of mining and GHG production with broader goals of decarbonizing the mining sector (Kirkey, 2014; Azadi et al., 2020). Worldwide, extraction of beach sand deposits rich in heavy mineral has been carried out by opencast mining by mechanized and manual mining methods. Mechanized mining is generally done using heavy earth-moving machineries (Force, 1991) and the principal sources of emissions are from consumption of energy in the form of diesel fuel in mining equipment resulting in direct emissions of greenhouse gases like carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), whereas manual mining is carried out with the help of manpower. There is also relationship between the processing of mineral products and climate change, related to fuel and electricity consumed by machinery in both extraction and processing (Norgate and Haque, 2012; Liu et al., 2015; Morrow et al., 2014). In green mining, technology such as manual mining and solar drying can lower the GHG emission during mining and drying processing in beach mining operation (Tadesse et al., 2022). Although the rapid rise in GHGs is a problem in India, there have been a limited number of studies attempting to quantify the intensity of GHGs in beach mineral mining and mineral drying process. The present study investigates the productivity and carbon foot print or CO_2 equivalent emission from the conventional mining methods and sand drying methods vis-a-vis those of green mining technology (like manual mining) and solar drying. This study aims to test whether manual mining and solar drying emit significantly lower GHG than mechanized methods.

2. METHODOLOGY

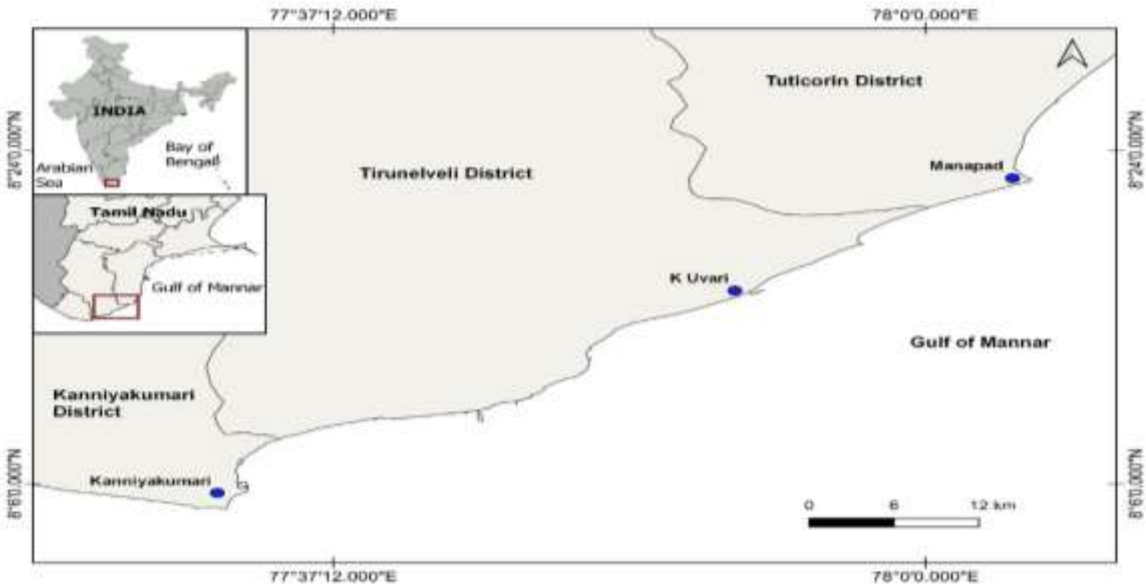
2.1. Study area

Data for the present study were collected from the company Transworld Garnet India Private Ltd, located in K. Uvari, Tirunelveli District, Tamil Nadu, India (Fig. 1). Both mechanized and manual mining of beach sands were carried out at the mining sites. Various data regarding the production efficiency of both mechanized and manual mining of beach sands for a known volume of beach sand were collected to compare the carbon foot print of the mining activity. Data were collected from the company inventory record for the year 2013. For conventional mining and mineral sand drying, data regarding the type of equipment used for mining, equipment used for drying of beach minerals, their efficiency, working hours, mining capacity, drying capacity and details about the fuel consumption were collected. Similarly, for manual mining, details about number of persons involved, work timing and their capacity of mining were collected. For solar drying, data regarding drying capacity and time taken were collected. Comparison study was carried out for conventional mining with manual mining to estimate their carbon foot prints. Similarly, carbon foot prints study was carried out for mechanized rotary mineral dryer and solar dryer (Fig. 2).

2.2. Investigation of Carbon foot print

In the present investigation carbon foot print or CO_2 equivalent emission from the mechanized mining events using Front-end loader and dryer operations in the Mineral Separation Plant were studied based on fuel consumption estimates and applying default emission factors (EPA, 2016). Simple calculation method was used to estimate the percentage saving of GHG emissions by green technology implemented compared to the fossil fuel-based operations. The greenhouse gas (GHG) value is expressed in emissions per ton of beach sand.

Fig. 1: Map showing the study area K. Uvari, located in the coastal track of Tirunelveli district



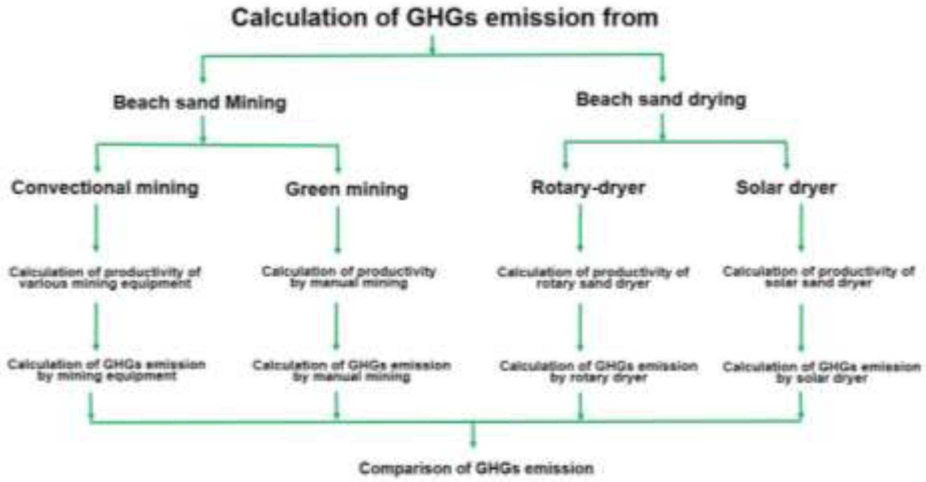


Fig. 2: Flow chart showing the methodology for the estimation of GHG emission for the present study

Method for quantification of GHG emissions

Estimation of total GHG emission can be done precisely and accurately through direct continuous emission monitoring of the tailpipe of the mining equipment. Routine collection of the data on direct continuous emission is not feasible hence for cost and practicality reasons Intergovernmental Panel on Climate Change (IPCC, 2000), (World Resources Institute, 2005) WRI/WBCSD (World Business Council for Sustainable Development) GHG Protocol 2005, recommends the use of calculation-based method of estimating direct Carbon dioxide (CO_2), Methane (CH_4) and Nitrous oxide (N_2O) emissions from mobile and stationary sources. In the present study Direct Greenhouse emission resulting from the operation of mobile mining equipment within an organization's inventory boundary was calculated based on EPA Greenhouse Gas Inventory Guidance for Direct Emissions from Mobile Combustion Sources (EPA, 2023). Mining equipment was categorised under non-road vehicles. Based on the fuel consumption records and actual fuel heat content (Table 1) CO_2 emission was calculated based on the following equation.

$$\text{Emissions} = \text{Fuel} \times \text{HHV} \times \text{EF2}$$

Where Emissions is the Mass of CO_2 emitted; Fuel represent Mass or volume of fuel combusted, HHV is Fuel heat content, in units energy per mass or volume of fuel; EF2 is CO_2 emission factor per energy unit. CH_4 and N_2O emissions were calculated based on the equation

$$\text{Emissions} = \text{Fuel} \times \text{EF5}$$

Where Emissions represent Mass of CH_4 or N_2O emitted, Fuel denotes Volume of fuel combusted and EF5 is CH_4 or N_2O emission factor per volume unit. For mining equipment front-end loaders data were gathered on the volume of fuel combusted, which is typically obtained from fuel consumption records.

CO_2 – equivalent emission calculation

Carbon foot print "the total set of greenhouse gas (GHG) emissions caused by an event" (Thurwachter et al., 1998) is often expressed in terms of the amount of carbon dioxide, or its equivalent of other emitted GHGs, calculated as carbon dioxide equivalent (CO_2e) using the relevant 100-year global warming potential (GWP100) (IPCC, 2014). CH_4 and N_2O emissions are multiplied by the respective global warming potential (GWP) to calculate CO_2–equivalent emissions. The GWP are 28 for CH_4 and 265 for N_2O from the Intergovernmental Panel on Climate Change, Sixth Assessment Report (AR6), 2021. To calculate the total CO_2 equivalent (CO_2 e) emissions, the CO_2 equivalent emissions from CH_4 and N_2O is summed with the emissions of CO_2. Method of estimating GHGs emissions in this study comprised the steps of i) selecting case study mining equipment and determining GHGs emission boundaries, and ii) quantifying GHGs emissions from the mining activity.

2.3. Case study

To study the GHG emissions from the mining activity, data on different mining equipment used in the industry and fuel consumption records were collected and used in the present study. The fuel used for operating the equipment in beach mining and mineral drying being diesel, the characteristics of diesel oil used for mining and separation processes were noted from the purchase records (Table 1).

Table 1. Characteristics of diesel oil based on fuel purchase records

S No	Characteristics	Specification	
		Indian Oil	**Bharat Petroleum**
1.	Density (Approx. g/cc at 15°C) max	0.845	0.853
2.	Sediment, % wt. max	0.05	0.05
3.	Sulphur Total % wt. max	0.25	0.25
4.	Water content, % vol. max	0.05	0.05
5.	Ash % wt. max	0.01	0.01
6.	GCV (KJ/Kg)	45,600	45,750
7.	HHV (mmBtu/gallon)	0.137	0.138

The BS (VI) standard value for diesel was 0.820 – 0.870 g/cc. Data were collected for mining an area of 1 ha of beach sand for a depth of 3 m. The bulk density of beach sand was 2.0 and the reserve was 60,000 m^3.

2.4. Conventional method of beach sand mining

Front-end loader was used for excavation of beach sand, which was attached with bucket. The bucket is indispensable for collection and loading of beach sand deposits on trucks. Totally three types of front-end loader or bucket loader were used for mining operation in Transworld Garnet India Private Limited, and they were JCB 433-4 Wheel loader, Caterpillar 966H and JCB 407 wheel loader.

Steps for estimating production of front-end loader

Step 1 Heaped bucket load volume (in LCM Loose Cubic Meter) was obtained from the manufacturer data sheet. Heaped bucket capacity ratings for Excavator buckets assume a 1:1 material angle of repose. Bucket capacity of excavator was measured in terms of either struck capacity or heaped capacity. Most commonly used description was heaped capacity which was taken in the present study to calculate the mining production.

Step 2 Material Type

In the present study, beach sand deposits fall under the material type of Sand and Gravel.

Step 3 Applying a bucket fill factor based on the type of machine and the class of material being excavated

For better estimation of the volume of material in one bucket load, the nominal bucket volume was multiplied by a bucket fill factor or bucket efficiency factor. The bucket fill factors for different materials are given by FEM (1988). Based on FEM (1998), for calculating the field productivity analysis, the correction factor used was between 0.9 -1.00, as the material of excavation is sand. So, the bucket fill factor used for the present analysis was 1.0.

Step 4 Calculation of Cycle Time

The time required to complete a series of operational tasks for the excavator is denoted as cycle time (Febrianti, 2018). The standard cycle times for different material types in accordance with the equipment's bucket size are presented in Table 2 and the standard cycle times for the loaders are given in Table 3.

Table 2. Standard cycles per hour for excavators (hydraulic shovels)

Material	**Machine size**					
	Small under 5 yard ($3.8\ m^3$)		Medium 5 – 8 yard (3.8-$7.6\ m^3$)		Large over 10 yard ($7.6\ m^3$)	
	BD	FD	BD	FD	BD	FD

Soft - sand, gravel, coal (cycles/hr)	190	170	180	160	150	135
Angle of swing (deg)	45	60	75	90	120	180
Adjustment factor	1.16	1.10	1.05	1.00	0.94	0.83

BD = Bottom Dump; FD = Front Dump

Table 3. Basic loader cyclic time

Loading conditions	**Basic cycle time (min)**	
	Articulated wheel loader	Track loader
Loose materials	0.35	0.30
Average material	0.50	0.35
Hard materials	0.65	0.45

Step 5 Estimating mining equipment front end loader productivity

Machine productivity is the mining equipment's ability to complete work and it is calculated in units of time (Dewi 2019, Fardila et al., 2017).

Calculating Productivity

Productivity is the work done by the mining equipment in units of time (m^3/hour). Excavator productivity during excavation process is calculated using the following formula (Fikri 2016).

$$Q = \frac{q \times 3600 \times E}{CM \times Fv} \qquad (\text{where } q = q1 \times K)$$

Where: Q = production per cycle (m^3), CM = Excavator Cycle Time, E = Tool Efficiency, q1 = Bucket Capacity, Fv = Conversion factor, K = Bucket Factor

Production (m^3/hr) = Bucket volume/cycle X Bucket fill factor X Cycles/hour X Job efficiency

Calculating effective working time of the different excavators in beach sand mining operations

Calculation of work time is the basic input for the calculation of work production and work volume of mining equipment front end loader. The formula used for calculation of work time (Fikri et al., 2016):

$$W = V/Q$$

Where: V = Volume of an excavation (m^3), Q = Front end loader production in every hour (m^3/hour)

Calculating volume of beach sand mined

The volume of beach sand mined was obtained from calculations and plan drawings from surveys and measurements in the field.

$$V = P \times L \times T \text{ x Bulk density of the soil}$$

The following notation:

V = Volume (m^3), P = Length, L = Width, T = Thickness

2.5. Estimating productivity of manual mining (green mining) of beach sand

Similarly, for the calculation of productivity by manual mining, the following formula was used.

Productivity (m^3/hr) = Volume of the basket x no. of persons x no. of times/hour

2.6. Conventional method of drying of beach sand

As heavy mineral sand often undergoes electrostatics and magnetic separation—processes which are highly sensitive to moisture content (Bruckard and Sparrow, 2010; Gupta and Yan, 2016), drying of beach mineral sand is a crucial step before the process of mineral separations.

Rotary dryer for beach sand drying

Rotary dryers are commonly used for the drying of beach mineral sand. In the present case study, diesel is the only fuel used to run the rotary dryer. The characteristics of diesel oil used are given in Table 1. Data on the rotary dryer productivity and fuel consumption were obtained from the ledger maintained in the office.

Estimation of productivity of solar drying of beach mineral sand

The calculation of productivity of solar drying of beach sand was done, considering the capacity of yards and the time taken for drying a known volume of beach sand.

Productivity (m^3/hr) = volume of sand dried/hours

3. RESULTS

3.1. GHG emission from conventional mining

Descriptions of the front-end loaders used in the present study

Three types of front-end loaders are used in mining of beach sand by Transworld Garnet India Private Limited, namely JCB 433-4 Wheel loader, Caterpillar 966H and JCB 407 wheel loader. JCB 433-4 wheel loader is designed to be fuel-efficient, and it can help reduce fuel costs by up to 10%. It has a JCB ecoMax 444 engine with a displacement of 4.44 litters and a maximum power of 125 horsepower. Caterpillar 966H front end loader is a versatile and powerful machine designed for a variety of mining and material handling tasks. It features a reliable Caterpillar C9.3 ACERT engine, delivering around 286 horsepower, which provides strong performance and efficiency. Generally, it consumes around 15 litres of fuel per hour, depending on usage conditions. Overall, the 966H is known for its durability, operator comfort, and adaptability, making it a popular choice in the mining industries. JCB 407 is a compact wheel loader designed for versatility and efficiency in various mining and material handling tasks. Powered by a JCB diesel engine, it typically offers around 64 horsepower. Its compact dimensions allow for easy navigation in confined spaces, such as mining sites. JCB 407 is ideal for applications in mining, landscaping, agriculture, and construction, offering a balance of power, efficiency, and manoeuvrability.

Productivity and effective working time of the different front-end loaders in beach sand mining operations

JCB 433-4 Wheel Loader showed a productivity of 192.98 m^3/hr with a working time of 39 days (Table 4), and Caterpillar 966H excavator obtained a productivity of 262.07 m^3/hr with a working time of 29 days. Performance of JCB 407 front end loader exhibited a productivity of 25 m^3/hr and it required a working time of 300 days to achieve the target production. The study clearly indicated fuel efficiency is higher for JCB 433-4 Wheel Loader 0.02 litres/ton for sand excavation.

Table 4. Showing productivity calculation for different front-end loader and their fuel consumption

S No	Specification	Mechanized mining		
		Front end loader		
1.	Equipment Type	JCB 433-4 Wheel Loader	Caterpillar 966H	JCB 407 wheel loader
2.	Bucket Capacity	3.1 m^3	4.21m^3	0.4m^3
3.	Work Efficiency	0.83	0.83	0.83
4.	Effective working hours	8 hours	8 hours	8 hours
5.	Maximum power	125 hp	286 hp	64 hp
6.	Soil type	Dry	Dry	Dry
7.	Fuel consumption	4.49 litre/hr	150.9 litre/hr	9.04 litre/hr
8.	Mining capacity (tons/hr)	192.975 tons/hr	262.07 tons/hr	25 tons/hr
9.	Reserve in the study area (m^3)	60,000 tons	60,000 tons	60,000 tons
10.	Total hrs required for mining the area (Working time)	310.92	228.95	2400
11.	Total no. of days to complete mining	38.87	28.62	300
12.	Productivity time calculation of Excavator (days)	39	29	300
13.	Total fuel consumption (l)	1400	3500	21700
14.	Fuel consumption litres per day	35.90	120.69	72.33
15.	Fuel consumption litres per hr	4.49	15.09	9.04

16.	Fuel consumption litres per ton	0.02	0.058	0.362

Quantification of GHG emissions due to conventional mining of beach sand

Appropriate emission factors issued by EPA Centre for Corporate Climate Leadership for Greenhouse Gas Inventories updated on June 5, 2024 were used in the present study. The emission factor of 73.96 kg CO_2/mmBtu, 1.01g CH_4/gallon diesel fuel and 0.94 g N_2O/gallon diesel fuel was used to estimate the emissions of GHGs from mobile combustion sources Front end loaders (Table 5). The carbon foot print values for conventional mining done by the different front-end loaders are 0.064 kg CO_2 e/ton, 0.158 kg CO_2 e/ton and 1.0045 kg CO_2 e/ton for JCB 433-4, Caterpillar 966H and JCB 407 respectively.

Table 5.Greenhouse gas emission intensity of front-end loader based mechanized mining

S No	Parameter	Mining equipment		
		JCB 433-4 Wheel Loader	**Caterpillar 966H**	**JCB 407-wheel loader**
1.	Diesel source	Indian oil	Indian oil	Bharat Petroleum
2.	Density (Approx. g/cc at 15°C) max	0.845	0.845	0.854
3.	HHV of the purchased diesel (mmBtu/gallon)	0.137	0.137	0.138
4.	HHV of the purchased diesel (mmBtu/litre)	0.0362	0.0362	0.0365
5.	Diesel consumption (l/hr)	4.49	15.09	9.04
6.	Diesel combustion (mmBtu /hr)	0.1625	0.546	0.33
7.	CO_2 emission, Kg CO_2/ton	0.0623	0.1541	0.97497
8.	CH_4 emission, g CH_4/ton	0.0062	0.01536	0.0965
9.	N_2O emission, g N_2O/ton	0.0058	0.0143	0.0898
10.	Equivalent CO_2 emission for calculated CH_4 emission, based on GWP (g CO_2/ton)	0.1738	0.4302	2.7014
11.	Equivalent CO_2 emission for calculated N_2O emission, based on GWP (g CO_2/ton)	1.531	3.789	23.795
12.	Carbon foot print of the event, Kg CO_2 e/ton	0.064	0.158	1.0015

3.2. GHG emission from manual mining

Productivity and effective working time of manual mining in beach sand mining operations

In manual mining, the work was carried out with the help of labours. The energy expenditure during manual mining is often measured in calories burned per hour (Table 6). While manual mining can be less energy-intensive than heavy machinery, it may also have lower output efficiency and slower production rates. There is no fuel consumption in manual mining, and hence there is no GHG emission.

Table 6. Showing productivity calculation for manual mining

S No	Specification	Manual mining
1.	Equipment Type	10 groups of workers 1 group = 10workers
2.	Bucket Capacity	15 kg
3.	Work Efficiency	-
4.	Effective working hours	8 hours

5.	Maximum power	21000 Kcal /hr
6.	Fuel consumption	-
7.	Mining capacity (tons/hr)	25 tons/hr

3.3. Rotary Dryer in mineral sand drying process

Rotary dryer was used to dry beach sand as it is effective in handling large volumes of material and can operate continuously. The drying process for beach sand typically involves reducing the moisture content of the sand to make it suitable for further processing in the Mineral Separation Plant. The temperature of the hot air that passes through the dryer is around 900^{o} C and the air flow rate should be carefully controlled. The study results showed an energy requirement of 1841.24 KW.h for uninterrupted operation of drying to eliminate the moisture content to produce 15 tons of dry sand in one hour. The total amount of fuel required to run the dryer is 180 litres per hour. The specification and productivity data of the dryer are shown in the Table 7.

Table 7. Performance and productivity data of rotary dryer in beach sand drying operation

S No	**Details**	**Beach Sand drying**
1.	Air flow	Parallel
2.	Dryer Dia (m)	1.5
3.	Length (m)	10
4.	Method of heating	Diesel
5.	Method of feed	Chute
6.	% of Moisture	6
7.	Bony dry basis	0.05
8.	Evaporation (kg/hr)	320
9.	Capacity (kg evaporation/ m^3 of dryer volume)	25
10.	Kcal supplied/kg water evaporation	1500
11.	Air temperature inlet	900
12.	Air temperature outlet	110
13.	Avg. Residence time in min	15
15.	Dryer capacity (tons/hr)	15
16.	Fuel consumption (l/hr)	180

Quantification of GHG emissions due to conventional drying of beach sand

The same emission factor used for beach mining processes is used for the conventional beach sand drying processes. The emission of CO_2, CH_4 and N_2O and their equivalent CO_2 for the rotary dryer based beach sand drying is given in the Table 8. The carbon foot print value of the conventional drying done by rotary dryer is 32.226 kg CO_2 e/ton.

Table 8. Greenhouse gas emission intensity of Rotary dryer-based beach sand drying process

S No	**Parameter**	**Rotary Dryer**
1.	Diesel source	Indian oil
2.	Diesel consumption (l/hr)	180
3.	Heat transfer rater (KWh)	1841.24 KW.h
4.	Diesel combustion (mmBtu /hr)	6.516

5.	Emission Factor (kg CO_2/mmBtu)	73.96
6.	Emission Factor (g CH_4/ mmBtu)	3.0
7.	Emission Factor (g N_2O/ mmBtu)	0.6
8.	Equipment production (m^3/hr)	15 tons/hr
9.	CO_2 emission, Kg CO_2/ton	32.121
10.	CH_4 emission, g CH_4/ton	1.303
11.	N_2O emission, g N_2O/ton	0.2606
12.	Equivalent CO_2 emission for calculated CH_4 emission, based on GWP (g CO_2/ton)	36.481
13.	Equivalent CO_2 emission for calculated N_2O emission, based on GWP (g CO_2/ton)	69.054
14.	Carbon foot print of the event, Kg CO_2 e/ton	32.226

3.4. Solar drying process of mineral sand and GHGs emission

Renewable energy based solar drying technique is climate friendly and contributes a solution to climate risks by reducing carbon foot print. Solar drying of beach sand is a natural and energy-efficient method used to remove moisture from sand, typically for purposes such as preparation of sand for mineral separation process, sandblasting, or other industrial applications. The process involves spreading wet or damp sand under the sun to allow evaporation of water, taking advantage of the sun's heat and ambient air movement to dry the sand. In general, solar drying of beach sand is a simple and effective technique, particularly suited for regions where sunlight is abundant and drying space is available. There is no GHGs emission in the solar drying process of beach mineral sand (Table 9).

Table 9. Performance data for solar drying in beach sand drying operation

S No	Details	Solar drying
1.	Capacity	15 tons/hr
2.	No. of Unit	13 drying yards Size 30 m L × 8 m B × 2.54 cm height
3.	Fuel used	Nil (Natural solar energy 5.8 KW/sq.m)
4.	Temperature	26 – 45°C, Average 37.1°C
5.	Heat transfer rate (KW)	1392 KW/yard
6.	Energy (MJ/hr)	5011.2 MJ/yard or 20.88 MJ/m2
7.	Impact on Environment	No GHG Emissions

3.5. Comparison of GHG emission form conventional mining and drying of beach sand with manual mining and solar drying of beach sand

The comparative analysis between conventional mining (mechanized) with manual mining of beach sand and conventional drying (rotary drying) with solar drying of beach sand indicates that use of diesel for operating mining equipment and rotary dryer leads to the emission of GHGs such as CO_2, CH_4 and N_2O into the atmosphere (Fig 3 ;Table 10). As manual mining is performed by labour without the use of fossil fuels, there is no direct emission of GHGs, though the productivity of manual mining is low when compared with the mechanized mining. Similarly, the productivity of solar drying depends on the intensity of sun radiation and it also needs more space in the form of drying yard.

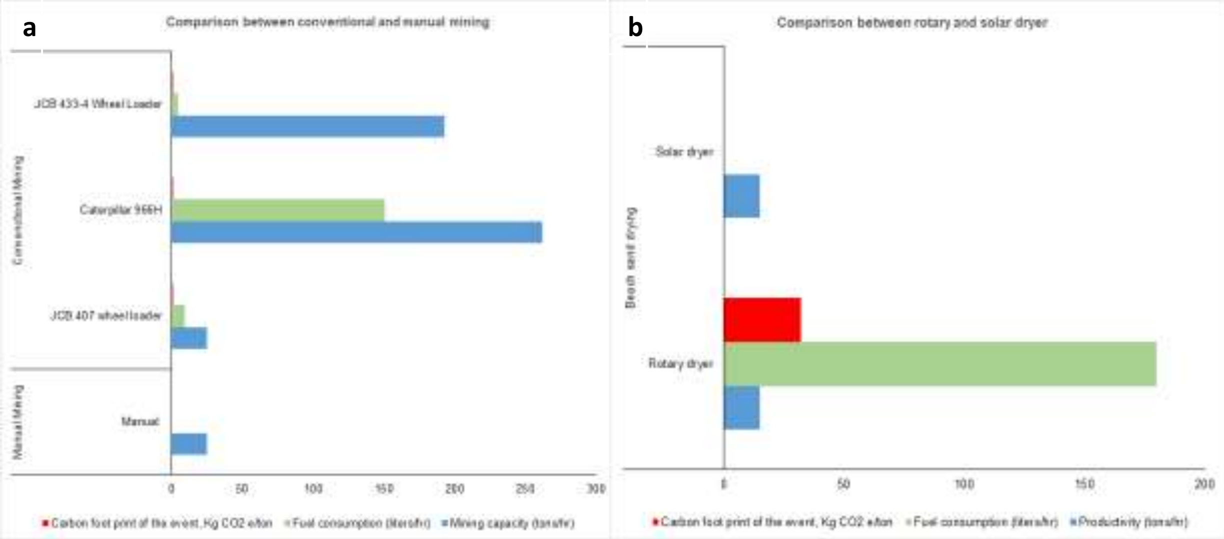


Fig. 3: Showing the comparison of productivity, fuel consumption and their respective GHG emission for conventional vs manual mining of beach sand and rotary drying vs solar drying of beach sand

Table 10. Showing the greenhouse gas emission intensity by mechanized and manual mining operation and beach sand drying

Criteria	**Beach sand mining**		**Beach sand drying**	
	Mechanized mining	**Manual mining**	**Rotary dryer**	**Solar dryer**
Productivity	High (25 to 192.97 tons/hr)	Low 25 tons/hr	15 tons/hr	15 tons/hr
Fuel consumption (Diesel)	High	None	180 l/hr	None
CO_2 emission, Kg CO_2/ton	0.0063 to 0.97497	Nil	32.121	Nil
CH_4 emission, g CH_4/ton	0.0062 to 0.0965	Nil	1.303	Nil
N_2O emission, g N_2O/ton	0.0058 to 0.0898	Nil	0.2606	Nil
Equivalent CO_2 emission for calculated CH_4 emission, based on GWP (g CO_2/ton)	0.1738 to 2.7014	Nil	36.481	Nil
Equivalent CO_2 emission for calculated N_2O emission, based on GWP (g CO_2/ton)	1.531 to 23.795	Nil	69.054	Nil
Carbon foot print of the event, Kg CO_2 e/ton	0.064 to 1.0015	Net Zero	32.226	Net Zero
Environmental Impact	Higher due to machinery and fuel usage	Low due to non-mechanized approach	Higher due to machinery and fuel usage	Low due to non-mechanized approach
Operational coast	High (fuel and equipment maintenance)	Lower (labour-based)	High (fuel and equipment maintenance)	Lower (based on sun intensity)

4. DISCUSSION

This research provides a comparative analysis of greenhouse gas (GHG) emissions and productivity for both conventional (mechanized) and manual methods of beach sand mining, as well as between rotary dryer and solar-powered sand drying techniques. The findings highlight notable environmental trade-offs linked to the employment of diesel-powered equipment in mining and drying processes when contrasted with labour-intensive or renewable energy alternatives.

4.1. GHG emissions from mechanized beach sand mining

The efficiency of mining operations is directly linked to the effectiveness and capability of the equipment employed (Agboola et al., 2020; Sanchez & Hartilieb, 2020). In the evaluation of three types of front-end loaders, the Caterpillar 966H showed the highest productivity at 262.07 tons/hr, but it also had the highest fuel consumption of 15.09 litres/hr, leading to a GHG emission intensity of 0.158 kg CO_2e for every ton of sand mined. The JCB 433-4 Wheel Loader, while less productive at 192.98 tons/hr, boasted of the lowest carbon footprint at 0.064 kg CO_2e per ton, attributed to its excellent fuel efficiency of 4.49 litres/hr or 0.02 litre per ton of sand. In contrast, the JCB 407, which had the lowest productivity at 25 tons/hr, was found to be the least efficient, generating a much higher GHG emission of 1.0045 kg CO_2e per ton, largely due to its significant fuel consumption of 0.362 litre per ton. High-capacity machinery with cost-effective operational characteristics is essential to sustain and enhance production levels (Morrison & Labrecque, 2020; Naghshbandi et al., 2022). These findings highlight the substantial variability in environmental performance across different machinery models and underscore the critical role of equipment selection in reducing GHG emissions. From an operational perspective, the JCB 433-4 presents the most balanced option, combining moderate productivity with low GHG emissions, making it suitable for sustainable mining applications (Rissman et. al., 2020).

4.2. GHG emissions from manual beach sand mining

Manual mining refers to the process of extracting minerals or resources using hand tools and physical labour, without the assistance of heavy machinery (Rupprecht, 2017). The energy used during manual labour is typically calculated in calories burned per hour, averaging around 21,000 calories/hr based on the work intensity. While manual mining can be less energy-intensive than heavy machinery, it may also have lower output efficiency and slower production rates. As there is no fossil fuel input, manual mining results in zero direct GHG emissions. Further, though manual mining is less energy-intensive than heavy machinery, the productivity was found to be on par with the lowest-performing mechanized option (25 tons/hr. equivalent to the JCB 407). The complete absence of fuel usage makes manual mining a carbon-neutral alternative for low-volume extraction needs. On the other hand, manual mining is often a livelihood for many in rural areas, providing essential income.

4.3. GHG emissions from Dryer-Based sand drying

A rotary dryer is a machine used for drying beach mineral sand. It uses a large cylinder drum rotating, fed with sand and hot air to heat and evaporate moisture. The heat is provided by a diesel burner. The drying process using a rotary dryer was found to be highly energy-intensive, consuming 180 litres of diesel per hour and emitting 32.226 kg CO_2e/ton of sand dried. CO_2 was the dominant contributor to the overall footprint, with additional emissions from CH_4 and N_2O contributing marginally to the total carbon equivalent. While rotary dryers perform consistently (15 tons/hr) and continuously, their reliance on fossil fuels makes them a major hotspot for GHG emissions in the mineral processing chain.

4.4. GHG emissions from solar drying

In contrast, solar drying offers a completely emission-free option, producing zero GHGs emissions and achieving a similar output (15 tons/hr) as rotary dryers. This method utilizes the natural energy of the sun, thus removing the requirement for fuel usage. Nevertheless, solar drying requires a significant amount of space, and its operational efficiency heavily relies on sunlight availability, which may restrict its use in areas with inconsistent solar conditions. However, in tropical or arid regions that experience high solar exposure, this technique delivers a climate-resilient and economical solution for drying mineral sands.

4.5. Comparative analysis

The comparative analysis shows that conventional mining and drying techniques of beach sand significantly contribute to carbon emissions, mainly due to the use of diesel-powered machinery. In contrast, green techniques such as manual mining and solar drying demonstrate the lowest environmental impacts, at the cost of lower productivity and longer processing times. These techniques not only support global climate mitigation objectives but also lead to long-term cost saving for operations. So, manual mining and solar drying can be employed whenever possible to reduce emissions and reliance on fossil fuels.

4.6. Ecological impact and recommendations.

The emissions of greenhouse gases (GHG) arising from mechanized beach sand extraction and the operation of rotary dryers present various serious ecological challenges. Foremost among them is the role they play in global climate change, primarily by increasing atmospheric levels of the gases CO_2, CH_4 and N_2O recognized for their significant global warming effect (Nellemann et al., 2009). The CO_2 released from the diesel could speed up climate change, potentially resulting in sea level rise, higher incidence of extreme weather events, and leading to habitat degradation and deterioration of air quality (UNEP, 2008). To mitigate these ecological impacts, green technologies such as manual mining have to be practiced wherever feasible, particularly in areas where labour resources are high. Solar drying technologies can be implemented in tropic and sub-tropic zones, where high solar irradiance is consistent.

5. CONCLUSION

This study has demonstrated clear distinctions in GHGs emissions and productivity levels between conventional (mechanized) mining and green technology (manual) mining for beach sand mining, and, similarly, between rotary dryer (conventional) and solar drying (green technology). Mechanized systems, particularly those relying on diesel-fuel equipment like front-end loaders and rotary dryer, contribute a considerable amount of carbon emissions, even though they offer higher productivity. Among the mining equipment assessed, JCB 433-4 was identified as the most environmentally efficient loader, achieving a balance between moderate output with low GHG emissions. In contrast, green technology such as manual mining and solar drying of beach sand presented carbon-neutral alternatives with zero direct GHG emissions. While these techniques yield lower output, they provide significant environmental benefits, particularly in areas with ample labour resources and high solar energy potential. The results highlight the potential of these low-carbon approaches as viable options for sustainable sand mining, particularly in small-scale or decentralized operations. So, decision-makers should encourage green mining technologies such as manual mining and solar powered drying for beach sand, where feasible, in alignment with global climate mitigation goals and support the transition to more sustainable mineral resources management practices.

ACKNOWLEDGEMENTS

The authors express their thanks to Transworld Garnet India Private Ltd, for providing data for the present research work and also thanks to Suganthi Devadason Marine Research Institute, Tuticorin for the research facilities.

6. REFERENCES:

1. Accounting, A. C. (2004). The Greenhouse Gas Protocol. World Resources Institute and World Business Council for Sustainable Development: Washington, DC, USA.
2. Agboola, O., Babatunde, D. E., Fayomi, O. S. I., Sadiku, E. R., Popoola, P., Moropeng, L., & Mamudu, O. A. (2020). A review on the impact of mining operation: Monitoring, assessment and management. Results in Engineering, 8, 100181.
3. Alvarizzy, M. H., Lusiana, L., Nuh, S. M. Productivity analysis of Excavator Heavy equipment in sand mining at PT Mitra Pasir Siliwangi. Jurnal Teknik Sipil, 24(2), 1083-1091.
4. Azadi, M., Northey, S., & Ali, S. H. (2020). Environmentally Responsible Mining: A New Paradigm for Mineral Development. Resources Policy, 65, 101561.
5. Bruckard, W. J., & Sparrow, G. J. (2010). "Physical separation of beach sand minerals." Minerals Engineering, 23(3), 261–267.
6. EPA. (2016) TSCA Chemical Substance Inventory, U.S. Environmental Protection Agency.
7. EPA,2023 (United States Environmental Protection Agency). Greenhouse Gas Inventory Guidance Direct Emissions from Mobile Combustion Source. 1-16.
8. Fardila D, Kelly LT, Moore JL, McCarthy MA (2017) A systematic review reveals changes in where and how we have studied habitat loss and fragmentation over 20 years. Biological Conservation, 212:130–138.
9. Fikri, E., Purwanto, P., & Sunoko, H. R. (2016). Life cycle assessment of household hazardous waste management options for Semarang City, Indonesia. International Journal of Environment and Waste Management, 17(2), 146-157.
10. Force, E.R. (1991). Geology of titanium mineral deposits. Geological Society of America, Special Paper. 259.
11. Gupta, A., & Yan, D. S. (2016). Mineral Processing Design and Operation: An Introduction. Elsevier.
12. (IPCC) Intergovernmental Panel on Climate Change. (2014). Climate Change 2014 Synthesis Report: Contribution of Working Groups I, II and III to the Assessment Report of the Intergovernmental Panel on Climate Change, IPCC, Geneva, Switzerland. 87.

13. (IPCC) Intergovernmental Panel on Climate Change. (2000). Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. 2-8.
14. (IPCC) Intergovernmental Panel on Climate Change (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report.
15. Kirkey, J. (2014). Eco friendly mining trends for 2014. http://www.mining-technology. c o m / f e a t u r e s / f e a t u r e e n v i r o n m e n t -friendly- mining-trends- for-2014-4168903/.
16. Liu, Z., Guan, D., Wei, W., Davis, S. J., Ciais, P., Bai, J., & He, K. (2015). Reduced carbon emission estimates from fossil fuel combustion and cement production in China. Nature, 524(7565), 335-338.
17. Morrison, D. M., & Labrecque, P. O. (2020, December). High-capacity production systems for Block Caving mines. In MassMin 2020: Proceedings of the Eighth International Conference & Exhibition on Mass Mining (pp. 703-715). University of Chile.
18. Morrow III, W. R., Gopal, A., Fitts, G., Lewis, S., Dale, L., & Masanet, E. (2014). Feedstock loss from drought is a major economic risk for biofuel producers. Biomass and Bioenergy, 69, 135-143.
19. Morrow, W. R., Gallagher, K. S., Collantes, G., & Lee, H. (2010). Analysis of policies to reduce oil consumption and greenhouse-gas emissions from the US transportation sector. Energy Policy, 38(3), 1305-1320.
20. Naghshbandi, S. N., Varga, L., & Hu, Y. (2022). Technology capabilities for an automated and connected earthwork roadmap. Construction Innovation, 22(4), 768-788.
21. Nellemann, C., & Corcoran, E. (Eds.). (2009). Blue carbon: the role of healthy oceans in binding carbon: a rapid response assessment. UNEP/Earthprint.
22. Norgate, T., & Haque, N. (2012). Using life cycle assessment to evaluate some environmental impacts of gold production. Journal of Cleaner Production, 29, 53-63.
23. Rissman, J., Bataille, C., Masanet, E., Aden, N., Morrow, W. R., Zhou, N., Elliott, N., Dell, R., Heeren, N., Huckestein, B., Cresko, J., Miller, S. A., Roy, J., Fennell, P., Cremmins, B., Koch Blank, T., Hone, D., Williams, E. D., de la Rue du Can, S., Helseth, J. (2020). Technologies and policies to decarbonize global industry: Review and assessment of mitigation drivers *through* 2070. Applied Energy, 266, Article 114848. https://doi.org/10.1016/ j.apenergy.2020.114848
24. Rupprecht, S. M. (2017). Bench mining utilizing manual labour and mechanized equipment-a proposed mining method for artisanal small-scale mining in Central Africa. Journal of the Southern African Institute of Mining and Metallurgy, 117(1), 25-31.
25. Solomon, S., Plattner, G.K., Knutti, R. and Friedlingstein, P. (2008). Irreversible climate change due to carbon dioxide emissions. Proceedings of the National Academy of Sciences of the United States of America. 106 :1704-1709.
26. Tadesse, G., Zimba, R., & Ndlovu, S. (2022). Sensor-based sorting: A green technology for mineral beneficiation. Resources Policy, 78, 102865.
27. Thurwachter, S., Bauer, D.J. and Sheng, P.S. (1998). Integration of environmental factors in surface planning: Part2-Multi-criteria hazard control, transactions of NAMRI. 5th edn. 26 : 115 -121.
28. Ting, D.S.K. & Hagh, A.V.B. (2023). Mitigating climate change. Proceedings of the Mitigating Climate Change 2021 Symposium and Industry Summit (MCC2021). https://doi.org/10.1007/978-3-030-9218-4.
29. World Resources Institute. (2005). World Greenhouse Gas Emissions: 2005. http:// www.wri.org/chart/world-greenhouse gasemissions-2005.
30. Yang, T., & Percival, R. V. (2009). The emergence of global environmental law. Ecology LQ, 36, 615.