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Development of alternative fuel for cement industries: The case of Messebo cement factory in Ethiopia

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ABSTRACT

The cement industry is struggling with dwindling fossil fuel resources and environmental issues related to climate change. This sector is known for its high energy consumption and generates significant CO2 emissions, accounting for 19% of global thermal energy consumption and 7% of CO2 emissions. For this reason, Cement industries are seeking to replace traditional energy sources with alternative fuels. This study aims to investigate and optimize alternative fuels, evaluating their chemical and physical properties, energy output, production capacity, effect on clinker quality, and impact on combustion flue gas emissions. The study shows that the alternative fuels meet or exceed the minimum international standard of 14 MJ/kg for net calorific value. Therefore, they could replace up to 40% of South African coal in the clinker pre-calcining process. Using alternative fuels such as P. j wood, P. j leaf, P. j charcoal, used tire, and optimized fuels could potentially reduce CO2 emissions by 2%, 9%, 9%, 21%, and 17% respectively. Therefore, policy makers and companies should strongly consider adopting these recommended alternatives.

Introduction

Cement industries are facing several challenges in the 21st century, including depleting natural fuel resources, raw material shortages, high demand for cement, and environmental concerns related to climate change. Modern cement was first introduced by Engineer J. Aspdin in 1824 with a production process consisting of three stages: raw material preparation, clinker calcination, and cement production (Xu et al., 2015) (Rahman et al., 2015). Cement production is very energy-intensive due to the high temperatures needed in the kilns. The manufacturing industry consumes over 19% of the world's energy, with 50% of their total costs going towards producing clinker in the pyro-process system (Supino et al., 2016). Pyro-processing results in significant heat loss and only a small amount of the energy produced from combustion is utilized efficiently.

The Messebo Cement factory is struggling because its primary fuel source, coal, is expensive and shipped from overseas. Only 4% of their sesame husk supply is utilized, with the remaining fuel needs covered by imported coal. The factory includes a 6-stage pre-heater, pre-calciner, rotary kiln, and grate cooler with a clinker calcining capacity of 3000 tons per day. To produce clinker, approximately 3260.4 MJ of energy per ton is used. This process is a significant cost factor in cement manufacturing, largely due to the use of imported coal. Typically, 60% of the coal goes into the clinker pre-calciner, with the remaining 40% being added to the main kiln's burner. The production of clinker requires varying amounts of energy based on the technology used. Using a wet process with internals is the most energy-intensive, requiring 6.8 MJ/kg of clinker production, while the dry process consumes the least amount of energy with less than 2.93 MJ/kg of clinker production. This type of energy saver kiln process is categorized under the 6-stage pre-heater plus calciner, which has a high-efficiency hot clinker cooler (Rahman et al., 2015). The operation of cement kiln system is affected by the chemical composition of the main components of the raw meal but also the combustion and consequently the fuel used.

Cement industries rely on different energy sources, including coal, coke, liquid and solid waste, used tires, and natural gas 4]. These fuels are considered alternative energy sources and are commonly used in high-temperature processes such as cement production. Alternative fuel utilization for the cement industry started in the 1980 s. Alternative fuels are made from waste and other sources used in many countries for over 35 years (Mokrzycki et al., 2003) (Mokrzycki et al., 2003). This study has focused on the characterization and optimization of two of the potential alternative fuels for cement industries, which are used tire and Prosopis Juliflora plant.

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In the 1980 s, tires became a popular alternative fuel for the cement industry due to relatively their high calorific value and low environmental impact (European, 1994). Scrap tires had already been used as a subsidiary energy source in Japan and the USA in 1976 and were subsequently adopted by developed countries. In 2003, the US threw away around 290 million tires, with 45% turned into tire-derived fuel (TDF). Cement factories used 58% of the TDF as fuel due to its lower cost compared to natural gas and coal. Out of the 1.8 million discarded tires, only 2.5 million were produced yearly in the US. In the USA 2.5 million tires were produced per year from this 1.8 million tires discarded as waste (Chinyama, 2012). The TDF has an environmental impact concerns but is less than fossil fuels (Chinyama, 2012). Landfilling and incineration are low-ranking waste disposal options that result in significant environmental emissions (Machin et al., 2017) (Mikulčić et al., 2016). However, they can be economically beneficial if the waste is efficiently recycled and used for energy or other purposes.

Prosopis Juliflora biomass is the second alternative fuel being considered in this study. Prosopis Juliflora is a fast-growing evergreen tree that is native to frost-free tropical regions of Mexico, South America, and the Caribbean. (Wakie et al., 2016). In the 1970 s, Prosopis Juliflora was introduced to east Africa by governmental and international development organizations to address environmental problems such as desertification. It provided firewood, prevented soil erosion, and served as food for animals. The plant's roots are able to grow deep to acquire water, and in 1960, researchers discovered the species' roots at a depth of 153 m near a mining pit. Prosopis Juliflora is a rapidly growing plant that has invaded the eastern region of Ethiopia, particularly the north part of the Afar landscape. It is displacing native plants that are beneficial, causing a lack of forage for livestock and harming traditional ways of life (Wakie et al., 2016).

T plant's negative impact on the economy and health of humans and animals is significant. Animals, such as cattle, are affected in various ways such as damage to indigenous grasses and trees commonly used for fodder, injury from thorns, and even death from consuming Prosopis juliflora pods (Sirmah et al., 2008) (Abdulahi et al., 2017). This plant harms humans by causing eye injuries from its thorns, increasing the spread of malaria, and reducing water content. Additionally, it has a negative impact on the economy. A 2016 study conducted in the Afar region across the Awsi, Gabi, and Hari zones found that removing biomass species completely would cost approximately USD 1.44 million per year to mitigate their negative impact (Tilahun et al., 2017). However, The plant has a high potential for energy due to its large availability, low-cost production, and ability to grow in dry environments. It is an exogenous species and can produce 2.5 tons of useful wood per hectare annually, even with insufficient rainfall (Chandrasekaran et al., 2020). In India, Prosopis Juliflora wood has many uses, including production of ethanol from stem wood, bio-oil from branches, and polymer composites.

Many tire repairers and traders in Ethiopia have accumulated large amounts of used tires, while the Prosopis Juliflora plant is abundant. However, the current use of these resources does not yield high-value products and there is untapped potential for energy recovery.

This paper aims to develop alternative fuel from locally available materials (Prosopis Juliflora plant and used tire) to support cement industries in diversifying their energy resources. By doing so, the cost of imported and unsustainable energy supply can be reduced. Using this alternative fuel could replace 40% of the 60% coal used in pre-calcining, helping to lower carbon emissions and the environmental impact of cement production. Replacing traditional fuels like coal with alternative options is a common practice amongst cement manufacturers, and can play a role in fighting global warming.

This study shows that cement industries and other energy-intensive sectors in Ethiopia and other African countries are not using alternative fuels. This research can be used by the research community to replicate methods for finding an optimized alternative fuel from different resources. It can also support companies in implementing such options to diversify their energy mix, reducing manufacturing costs and environmental impacts. This research output should also provide valuable insights for policy makers in order to support and facilitate the development of locally available raw materials such as waste and invasive plants for energy generation purposes.

The paper is organized in five sections. Section 2 outlines the research methodology, including sample preparation, carbonization, and analysis, while also identifying the materials used. Section 3 presents the results, including raw material characterization and alternative fuel optimization. Section 4 provides interpretation and discussion of the results. Section 5 presents concluding remarks.

Methods and materials

Methods

Prosopis juliflora biomass sample preparation

The Prosopis juliflora (P.j) was gathered from the Alamata district in the Tigray Regional state of Ethiopia. The raw material was cleaned and dried in the sun to eliminate any contaminants and moisture. The dried P.j was manually cut into pieces for pulverization and carbonization. Fig. 1 shows three years old Prosopis juliflora plant at Alamata, and

Fig. 1. Prosopis Juliflora Tree and Wood.

Fig. 2. Prosopis Juliflora charcoal (a) and charcoal powder (b).

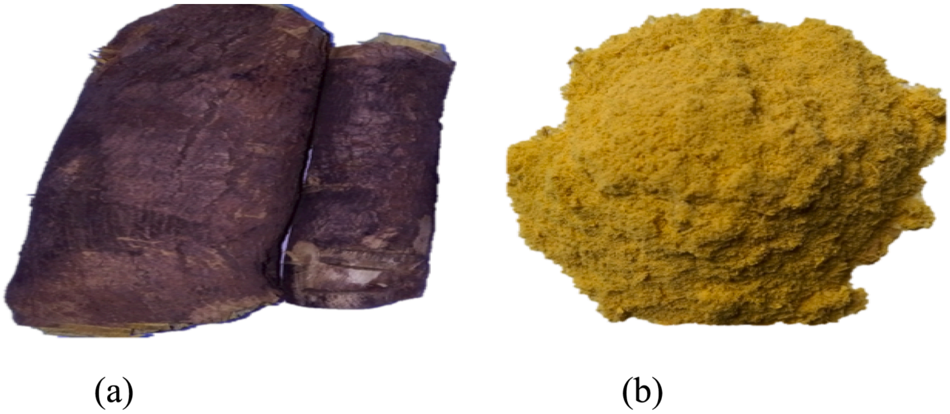

Fig. 3. Prosopis Juliflora wood (a) and wood powder(b).

Prosopis juliflora cut wood.

i. Charcoal sample preparation

The Prosopis juliflora was carbonized using an earth pit reactor, the traditional and widely used method in Ethiopia. Samples of wood were cut to be 10 cm long and more than 8 cm in diameter. To prepare for pulverization and carbonization, a 0.5-meter high and 1.5-meter wide hollow was created in the ground. To prevent airflow that could cause complete combustion and turn the wood into ash, leafy materials and soil lumps were used to fully cover and seal the top of the pit. Initially, the production of charcoal results in thick white smoke. During dehydration, the charcoal emits thick, white and moist smoke. Finally, the smoke turns yellow, marking the completion of the carbonization process. The charcoal is then retrieved from the earth pit. The hot charcoal is spread on the ground and covered with loose soil to cool and prevent re-burning due to oxygen on the surface.

The laboratory at the cement plant was used to prepare the fuel sample by crushing it into small particles ranging from 120 μm to 60 μm. This size reduction aims to increase the density of the biomass, thus enhancing its burnability (Mu, 2019). Measurements for Prosopis juliflora charcoal samples were taken from the same prepared sample for all tests, including calorific value, proximate analysis (moisture, ash, volatile matter, and fixed carbon), and ultimate/elemental analysis (hydrogen, sulfur, carbon, and nitrogen). Fig. 2 shows two types of charcoal: prepared sample and powder. The left side displays P. j charcoal, while the right side shows charcoal that has been crushed into small particles.

ii. Prosopis juliflora wood sample preparation

The woody part of Prosopis juliflora was ground into a fine powder after the bark was removed. This was done to increase the burnability of the biomass. The grinding was done manually, and Fig. 3 shows the dry wood on the left and the ground powder on the right.

iii. Bark fuel sample preparation

Bark fuels are commonly burned for direct heat in industrial drying, and to produce steam for heating, processing, or electricity generation in boiler furnaces. The bark used in this study was peeled from the Prosopis Juliflora stem, and both wood and bark have a high volatile substance content in terms of energy. The bark was dried using an open air system, and a sample was taken from the dried wood for analysis, as shown in Fig. 4.

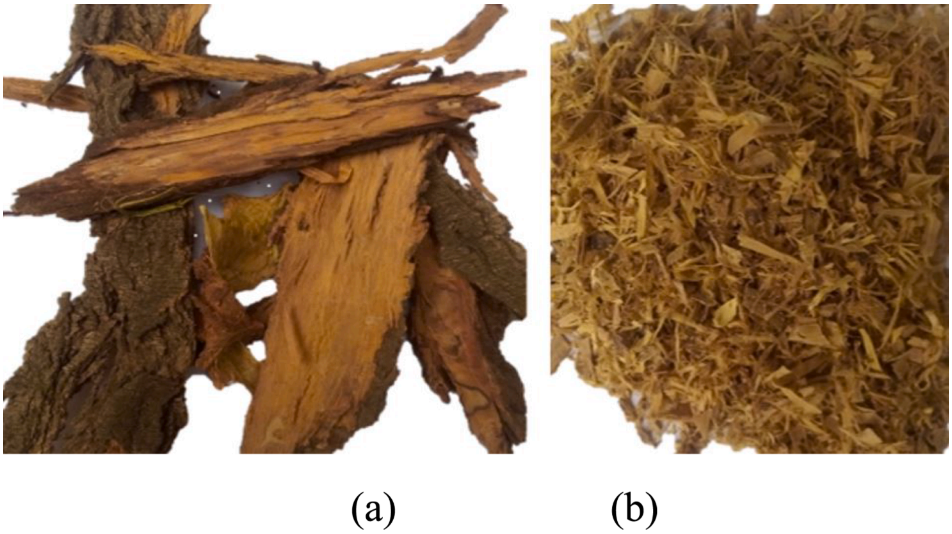

Fig. 4. P. J bark (a) and grinded bark (b).

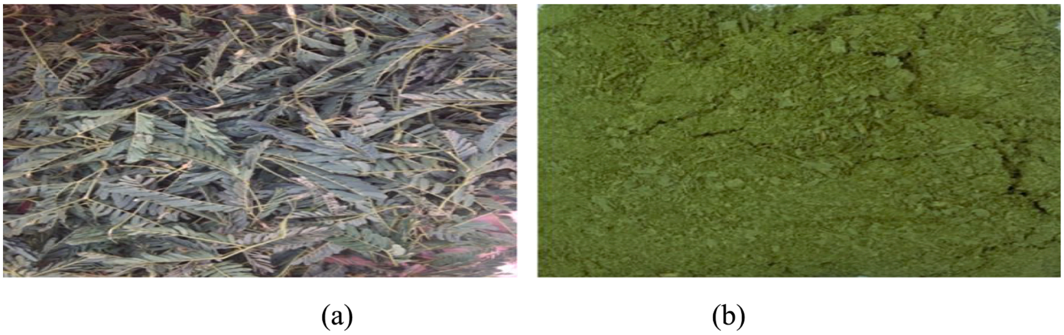

Fig. 5. P. J leaf (a) and leaf powder (b).

iv. Leaf sample preparation

Small pairs of leaves were taken from the tree or branch and unwanted particles were removed before grinding them into a fine powder. This powder was then used to analyze the chemical, physical, and thermal properties of the leaves (see Fig. 5).

Used tire sample preparation

A sample of waste tires was collected from three places in Mekelle city, then cleaned to remove impurities. To ensure compatibility with the current fuel source, the tire sample was ground to the same size as coal powder used in the factory (see Fig. 6). The fuel particle size for pre-calcining must fall within the range of 60 μm-200 μm (Rehn et al., 2019).

Calorific value measurement

The energy content of Prosopis juliflora biomass and used tire samples were measured by taking the following mass for each sample (0.5 g, 0.5005 g, 0.500 g, 0.501 g and 0.501 g Prosopis juliflora (charcoal,

Fig. 6. Used tire scrap (a) and tire powder (b).

wood, leaf, and bark) and used tire sample mass were taken respectively). These samples mass was put in clean crucible, and measured using digital balance in Messebo cement factory chemical laboratory. The gross calorific value of the samples was measured with an adiabatic bomb calorimeter, using the American Society for Testing and Materials (ASTM) international method D3174.

Proximate analysis measurement

The collected samples underwent proximate analysis, measuring moisture content, volatile matter, ash content, and fixed carbon at the Messebo Cement Factory PLC chemical laboratory. Samples were taken from each batch, and the test followed the ASTM 93 standard.

Ultimate analysis measurement

The chemistry department at Addis Ababa University was used to conduct the elemental composition analysis on samples of used tires and Prosopis Juliflora biomass (including wood, leaf, bark, and charcoal). The samples were dried, crushed, and analyzed using an elemental analyzer. For each sample, 5 mg mass was taken after being dried or weighed in a tin crucible with vanadium pentoxide catalyst. Placing the sample powder in the tin crucible and adding oxygen triggers a strong exothermic reaction in the reactor, increasing the temperature to 900 °C and causing the sample to combust. The resulting products, along with the catalysts, pass through the reactor where oxidation is completed. This process reduces nitrogen oxides and sulfur trioxide to elemental nitrogen, while retaining sulfur dioxide and oxygen excess. The gas mixture containing N2, CO2, H2O, and SO2 was separated in the chromatographic column. The eluted gases were directed to the thermal conductivity detector. The Eager 300 software processed the electrical signals and provided the percentages of nitrogen, carbon, hydrogen, and sulfur in the sample.

Energy balance of fuel combustion

Energy balance for fuel combustion is indicated in Fig. 7.

Assumptions considered for the energy balance of fuel combustion are given below.

- The air–fuel mixture will be a dry mixture
- Flue gases enthalpy must be unchanged with time (consistent), and calorific value also as well
- Net calorific value (NCV) of fuel has been considered
- The flue gases enthalpy consists only sensible heat
- The system is closed (adiabatic)
- There is no; kinetic energy $\Delta K_E = 0$, potential energy $\Delta P_E = 0$, work done W = 0, and it is steady state.
- C_v, H_R, and H_P all are considered with standard pressure and temperature (1ATP, and 298.15 k or 25 °C

Table 1
P.j biomass and used tire measured gross and net calorific values.

Sample type	Mass (g)	T_i(°K)	T_f(°K)	GCV (MJ/kg)	NCV (MJ/kg)
P. j charcoal	0.500	2.564	4.870	30.5	29.90
P. j wood	0.5005	2.393	3.262	16.18	14.37
P. j bark	0.501	2.316	3.157	15.68	13.45
P. j leaf	0.500	2.371	3.371	18.64	16.97
Used tire	0.501	2.433	4.362	36.19	34.70

Alternative fuel optimization

The alternative fuel model was optimized using Microsoft 2016 Excel Solver program to maximize thermal energy output while adhering to emission standards for European and North American cement manufacturing. The blend fuel yielded the highest thermal energy output, which depends on the mass and net calorific value. However, the optimized thermal energy output was constrained by the quantity and calorific value of the alternative fuel.

1. Decision variable

The amount of alternative fuel mass was used as a decision variable to determine the maximum thermal energy production and net calorific value of the fuel mixes. Flue gas emissions during combustion were also affected by the amount of alternative fuel mass used. The goal is to increase the net calorific value of alternative fuels by managing flue gases.

2. Constraints

This study considered the emission or flue gas produced by fuel combustion as the second optimization constraint. The maximum emission constraints were based on the benchmark of European and North American cement manufacturing emission standards, which are also part of the KYOTO protocol convention.

Materials

The materials employed during the raw material preparation and experimentations were water jacket (volume of 1.8 L) capacity, oxygen, vessel, fuse wire, battery, thermometer, silica crucible, cotton, Meter, Clock, Shovel, Fork, cutter, crusher mill, sieves, electronic balance, crucibles, oven, Vecstra muffle furnace, thermo-gravimetric analyzer, bomb calorimeter. Experimental equipment was obtained from Messebo cement factory, Addis Ababa University where laboratory analysis was performed. Chemicals and reagents used during series of experiments were benzoic acid, Helium (carrier gas), oxygen, Agate mortar and pestle, Chamber for freeze drier, Desiccator and silica gel, Mill, Sample holder, Spatula or spoon, Laboratory paper, Kim wipes (chemical laboratory wipes), Spring tweezers, Tin containers (set of 100) and Eager 300 software.

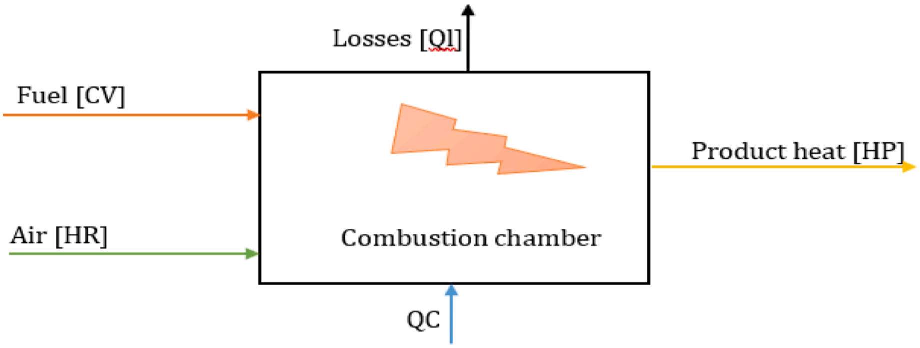

Fig. 7. Schematic diagram of combustion reaction energy balance.

Results

Fuel combustion in clinker pre-calcining process

Messebo Cement Factory uses a 6-stage process involving a preheater cyclone, calciner, and high-efficiency cooler to produce an average of 3000 Tons of clinker per day. The typical thermal energy consumption for calcining one kilogram of clinker in this process should be 2.93 MJ. (Rahman et al., 2017). However, Messebo Cement Factory consumes an average of 3.2604 MJ of specific thermal energy per kilogram of clinker in its calcining process. The coal it uses is imported from South Africa.

Calorific value of the alternative fuels

Table 1 shows the test results for the gross and net calorific values of P.J biomass and used tire fuels. Used tire had the highest GCV value at 36.19 MJ/kg, followed by P.J. Charcoal at 30.5 MJ/kg, and P.J. bark had the lowest GCV value at 15.68 MJ/kg.

Proximate analysis of the alternative fuels

Table 2 displays the moisture content values for each sample. The measurements were taken by heating the samples on a stove for a specified time period and determining the weight loss. The volatile matter was measured using a Vecstra muffle furnace. The samples, including charcoal, wood, leaf, bark, and used tires, were crushed and placed in a crucible on the lid, then heated at 950 °C for 7 min in accordance with the ASTM international 93 standard. To calculate the fixed carbon, the moisture content (%), volatile matter (%), and ash (%) are added together. Results show that P. j charcoal has the highest fixed carbon at 78.79%. P. j bark has the highest ash at 8.44% and moisture content at 6.45%, while P. j leaf has the highest volatile matter at 74.71%.

Ultimate analysis of the alternative fuels

Table 3 displays the elemental composition of P. J biomass and used tire samples. The results indicate that used tire possesses the highest carbon content (84.57%), while P. J bark possesses the lowest carbon content (41.16%).

Ultimate and proximate analysis of the South Africa coal

Table 4 displays the elemental composition, heating value, and proximate analysis of the current S.A. coal used at the factory. The imported coal has an net calorific value (NCV) of 27.2 MJ/kg.

Alternative fuel optimization

P.J. bark is not suitable for optimization due to its low NCV of 13.45 MJ/kg, which is below the internationally recognized minimum of 14 MJ/kg for alternative fuels. All other potential alternative fuels, which have an NCV greater than 14 MJ/kg, are being considered for optimization. By optimizing the fuel mix (see Fig. 8), to include 35% Prosopis Juliflora charcoal, 64% used tire, and 1% Prosopis Juliflora leaf, 1059.2 MJ of thermal energy can be generated for pre calcining 1.34 tons of clinker. Prosopis Juliflora wood was not included due to its low calorific value and high flue gas emissions. The fuel optimization process resulted in Prosopis Juliflora wood having zero optimized mass and thermal energy.

Table 3
Elemental compositions of P. J biomass and used Tire.

Ultimate analysis (Elemental composition) wt.%					
Element	Samples				
	P. J wood	P. J Charcoal	P. J bark	P. J leaf	Used tire
N (%)	8.09	11.83	0	2.897	5.65
C (%)	43.01	83.24	41.16	46.97	84.57
H (%)	6.71	2.51	7.87	6.42	6.84
S (%)	0.13	0.09	0.02	0.09	0.07
O (%)	42.05	2.33	50.96	43.62	2.87
Total	100	100	100	100	100

Table 4
South Africa coal elemental composition, proximate analysis, and NCV.

Fuel type	Ultimate analysis (%)		Proximate analysis (%)		NCV (MJ/kg)
South Africa coal	Carbon	83.5	Volatile matter	25.9	27.2
	Hydrogen	5.4	Fixed carbon	55.5	
	oxygen	8.4	Ash	10.2	
	Nitrogen	1.7	Moisture content	8.4	
	Sulfur	1.0			

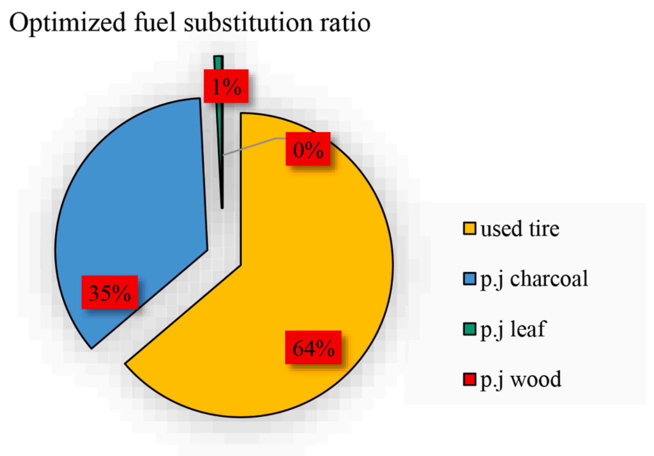

Fig. 8. Optimized alternative fuel substitution ratio.

The optimization result shows that the substitution ratio of P.J wood-alternative fuel is zero. Wood has a net calorific value of 14.37 MJ/Kg, which is lower than other proposed alternative fuels. Despite this, wood can still be used as an alternative fuel for the pre-calcining process because it meets the international standard for alternative fuels in the cement industry.

Table 2
Proximate analysis of the different alternative fuels.

Sample type	Mass (g)	Moisture content (%)	Volatile matter (%)	Ash (%)	Fixed Carbon (wt. %)
P. j charcoal	1.00	2.15	15.79	3.27	78.79
P. j wood	1.00	4.64	74.68	3.20	17.48
P. j bark	1.00	6.45	74.25	8.44	10.86
P. j leaf	1.00	5.75	74.71	6.73	12.81
Used tire	1.00	0.59	6.90	7.79	27.62

Table 5
S.A coal stoichiometry combustion reaction mass balance.

Elem	Wt. %	Mc wt	El mass/ kg fuel	Kmole/kg fuel	Req O_2/ kg fuel	Product Type	Product Mass /kg fuel
H	5.4	1	0.054	0.054000	0.432	H2O	0.4860
C	83.5	12	0.835	0.069583	2.227	CO_2	3.0617
N	1.7	14	0.017	0.001214	0.000	N_2	0.0170
S	1	32	0.01	0.000313	0.010	SO_2	0.0200
O	8.4	16	0.084	0.005250	−0.084	–	–
Total	100		1		2.585		3.585

Mass and energy balance of the fuel combustion reactions

Understanding the alternative fuel's mass and energy balance is important to determine its fuel consumption for every kg of clinker produced, flame temperature, and emissions, compared to the existing coal. This data is crucial in determining the optimized fuel type and ratio, based on the factory's current coal usage and international standards.

Mass balance of the fuel combustion reactions

Fuel is combusted in the clinker pre calcining process chamber. This combustion reaction needs mass balance in clinker pre calcining process. Five basic determinant features of fuel combustion properties are; carbon (C = 12), hydrogen (H = 1), oxygen (O = 16), Sulphur (S = 32), and nitrogen (N = 14). In the reactant side total mass balance for one-kilogram of fuel combustion elemental weight (kg/kg of fuel), mole fraction (kmole/kg fuel), and oxygen required for each element's combustion was calculated. In the product side, associated product type and the amounts of associated products (kg/kg of fuel), which are generated, while one kg of fuel is combusting in the pre calcining process is shown in the subsequent sections.

Table 5 shows the stoichiometric combustion reaction mass balance for existing coal. The elemental weight in the fuel (kg/kg of fuel), mole fraction in the fuel (kmole/kg of fuel), oxygen is required for combustion reaction as well as associated product type and the amount of associated product (kg/kg of fuel) is calculated as well. The elemental composition of one kilo-gram of S.A coal has, carbon 0.835 kg carbon, which requires 2.227 kg oxygen/ (kg of fuel) producing 3.062 kg carbon dioxide/ (kg of fuel), 0.054 kg hydrogen, which requires 0.432 kg oxygen/ (kg of fuel) producing 0.486 kg water/ (kg of fuel), 0.017 kg nitrogen /(kg of fuel), which requires 0 kg oxygen producing 0.017 kg nitrogen dioxide /(kg of fuel), 0.01 kg sulfur/ (kg of fuel), which requires 0.01 kg oxygen /(kg of fuel) producing 0.02 kg sulfur dioxide /(kg of fuel), and 0.084 kg oxygen /(kg of fuel) is used to oxidize the combustions reaction.

Similarly, the P.J charcoal, used tire, P. j wood, P. j leaf, and the optimized fuel stoichiometry combustion reaction mass balance are given in Table 6, Table 7, Table 8, Table 9, Table 10 respectively.

Energy balance of the fuel combustion reactions

Energy was balanced for all alternative fuels and coal during combustion. The maximum excess air ratio for alternative fuels was 30%, which falls within the acceptable range for a rich mixture. The European benchmark for excess air ratio during cement clinker calcining using dry rotary kiln technology is between 10% and 30% (Mikulčić et al., 2013). These air–fuel proportion are essential for the formation of the clinker phases and the quality of clinker as well as finished cement (Mikulčić et al., 2013). All the alternative fuel energy balance for reactant side and product side are shown in Table 11.

The process of calcining one kilogram of clinker requires 3.2604 MJ of thermal energy. Therefore, one ton of clinker calcining process requires 3260.40 MJ of thermal energy. Approximately 60% (1956.24 MJ) of this thermal energy is used in the pre-calcining process and about 40% (782.496 MJ) of the 60% thermal energy can be substituted with alternative fuels.

Depending on the type of chemical composition nature of the fuel, different fuels have various thermal energy generation capacities (see Fig. 9). South Africa coal is used as benchmark for evaluating the other alternative fuel thermal energy generating capacity. The thermal energy of optimized fuel, used tire, and P. J charcoal increased by 21.3%, 27.6%, and 9.9%. Meanwhile, P. j bark, P. J wood, and P. J leaf had decreased thermal energy by 50.5%, 47.2%, and 37.6%. Therefore, optimized fuel, used tire, and P. J charcoal are suitable as alternative fuels for the pre-calcining process.

Discussions

Alternative fuel flame temperature

The pre-calcining chamber has clinker temperatures ranging from 950 °C to 1150 °C. The fuel combustion flame temperature in the same chamber is slightly higher than the clinker temperature. Fig. 10 displays the flame temperature of different fuels, including South African coal. The optimized fuel has a flame temperature of 1390 °C, while Prosopis Juliflora charcoal has a temperature of 1395 °C. Juliflora's wood has flame temperature of 1256 °C, Prosopis juliflora leaf has flame temperature of 1314 °C, and used tire has flame temperature of 1391 °C, which are greater than the required standard temperature of the calcining chamber. However, the flame temperature of the fuels is controlled using excess air in order to match the required flame

Table 6
P. J charcoal stoichiometry combustion reaction.

Elem	Wt.%	Mc wt	El,mass/kg fuel	Kmole/kg fuel	Req O_2/kg fuel	Product Type	Product Mass/kg fuel
H	2.506	1	0.02506	0.02506	0.20048	H_2O	0.22554
C	83.24	12	0.83	0.069365	2.21968	CO_2	3.05206
N	11.83	14	0.11832	0.00845	–	N_2	0.11832
S	0.09	32	0.0009	0.000028125	0.0009	SO_2	0.0018
O	2.334	16	0.02334	0.00145875	−0.02334	–	–
Total	100		1		2.39772		3.4

Table 7
Used tire stoichiometry combustion mass balance.

Elem	Wt.%	Mc wt	El, mass/kg fuel	Kmole/kg fuel	Req O_2/kg fuel	Product Type	Product Mass/kg
H	6.839	1	0.06839	0.06839	0.54712	H_2O	0.61551
C	84.58	12	0.84568	0.070473	2.2551	CO_2	3.10083
N	5.654	14	0.05654	0.00403857	0	N_2	0.05654
S	0.07	32	0.007	2.187	0.0007	SO_2	0.0014
O	2.869	16	0.029	0.00179	−0.0287	–	–
Total	100		1		2.7743		3.773

Table 8
P. juliflora wood stoichiometry combustion mass balance.

Elem	Wt.%	Mc wt.	El, mass/kg fuel	K mole/kg fuel	Req O_2/kg fuel	Product Type	Product Mass/kg
H	6.711	1	0.06711	0.06711	0.53688	H_2O	0.60399
C	43.013	12	0.43013	0.0358	1.147013	CO_2	1.577
N	8.093	14	0.08093	0.00578	0	N_2	0.08093
S	0.131	32	0.00131	0.0000405	0.00131	SO_2	0.00262
O	42.052	16	0.42052	0.0262825	−0.42052	–	–
Total	100		1		1.26468		2.26468

Table 9
P. juliflora leaf stoichiometry combustion mass balance.

Elem	Wt.%	Mc wt.	El, mass/kg fuel	K mole/kg fuel	Req O_2/kg fuel	Product Type	Product Mass/kg
H	6.423	1	0.06423	0.06423	0.51384	H_2O	0.07
C	46.9	12	0.46969	0.03914	1.2525	CO_2	1.722
N	2.897	14	0.02897	0.00207	0	N_2	0.02897
S	0.091	32	0.00091	0.000028	0.00091	SO_2	0.00182
O	43.62	16	0.4362	0.0273	−0.4362	O_2	–
Total	100		1		1.331		1.823

temperature of the chamber and its associated clinker temperature. The European cement manufacturing standard requires the excess air ratio for cement clinker pre-calcining process to be between 10% and 30% in dry rotary kiln clinker calcining technology. This is critical for the formation of clinker phases and the quality of the final cement product (Mikulčić et al., 2013). The highest temperature in the pre-calcining chamber for clinker is 1150 °C, which is lower than other fuels and coal in South Africa. However, excess air is used to bring these temperatures to the standard level.

Evaluation of the emissions from the alternative fuels

The study compared emissions from potential alternative fuels to international cement factory standards and the South African Coal currently used by Messebo Cement Factory, the subject of the case study. This comparison validates the recommended alternative fuels and ensures they meet international standards and are compatible with the coal used by the cement industry in the case study. This enables the alternative fuels to be readily used as substitutes for conventional fuels like South Africa Coal. The international standards of the different emissions utilized as a comparison for the alternative fuel are given in Table 12.

a) Carbon dioxide

Cement industries emit 7% of the world's carbon dioxide into the environment (Mikulčić et al., 2013). Over 50% of these emissions happen during the chemical reaction process of cement production, with almost 40% coming from burning fuels. The remaining 10% of emissions come from transportation and electricity consumption (Mikulčić et al., 2013). To cut CO2 emissions in the cement industry, employing renewable energy sources like alternative fuel in the clinker pre calciner process is helpful (Mikulčić et al., 2013).

The CO_2 emission generated from the alternative fuels considered in this study is compared with the standard emission of a maximum of 99 kg CO_2 per ton of clinker based on the burning of 40% alternative fuel of the 60% fuel required in the pre calcining process (CCIEBSR, 2019) (Canada and Association, 2009). Based on the results, the combustion CO_2 emission generated by all of the alternative fuels analyzed in this study is less than the maximum acceptable standard as shown in Fig. 11. The zero substitution shows the standard emission without the use of alternative fuels while the other values indicate substitution percentage versus emissions until the allowable 40% of the 60% fuel utilized in the pre-calcining process.

The study compared CO2 emissions from various alternative fuels to South Africa's coal, which is currently used in the Messebo Cement Factory. The coal is substituted up to 40% for the clinker pre-calcining process. By substituting optimized fuel, used tire, P.J. charcoal, P.J. leaf, and P.J. wood at a 40% substitution rate, CO2 emissions have been

Table 10
Optimized fuel stoichiometry combustion reaction mass balance.

Elem	Wt.%	Mc wt.	El, mass/kg fuel	K mole/kg fuel	Req O_2/kg fuel	Product Type	Product Mass/kg
H	5.3	1	0.05318	0.05318	0.425	H_2O	0.4786
C	83.7	12	0.83727	0.06977	2.233	CO_2	3.0700
N	7.8	14	0.07789	0.00556	0.000	N_2	0.0779
S	0.5	32	0.00480	0.00015	0.005	SO_2	0.0096
O	3.1	16	0.03089	0.00193	−0.031	–	–
Total	100		1		2.6321		3.70

Table 11
Combustion reactant and product energy balance (kJ/kg fuel).

Product	**S. A Coal**	**Used Tire**	**P. J charcoal**	**P. J wood**	**P. J leaf**	**Optimized fuel**
Carbon dioxide	5265.70	5223.47	5157.03	2354.08	2712.50	5166.0
Water (vapor)	1541.07	1909.78	702.03	1653.82	1672.70	1483.5
Nitrogen	20400.56	26646.36	23232.79	10100.24	11998.41	25302.5
Sulphur dioxide	34.40	2.36	3.04	3.91	2.87	16.2
Oxygen for excess	195.83	1236.44	1071.73	334.96	556.48	1171.9
Hp	27437.55	35018.41	30166.62	14447.01	16942.95	33140.0
(LHV + HR)	27437.55	35018.41	30166.62	14447.01	16942.95	33140.0

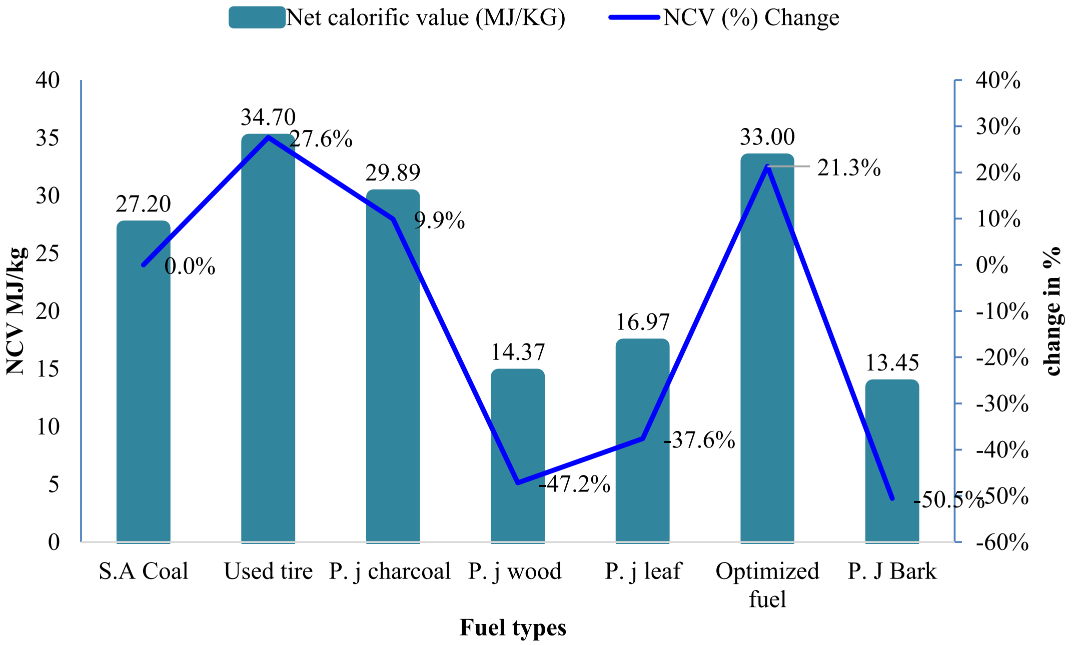

Fig. 9. Comparison of thermal energy generation capacity of the different fuels.

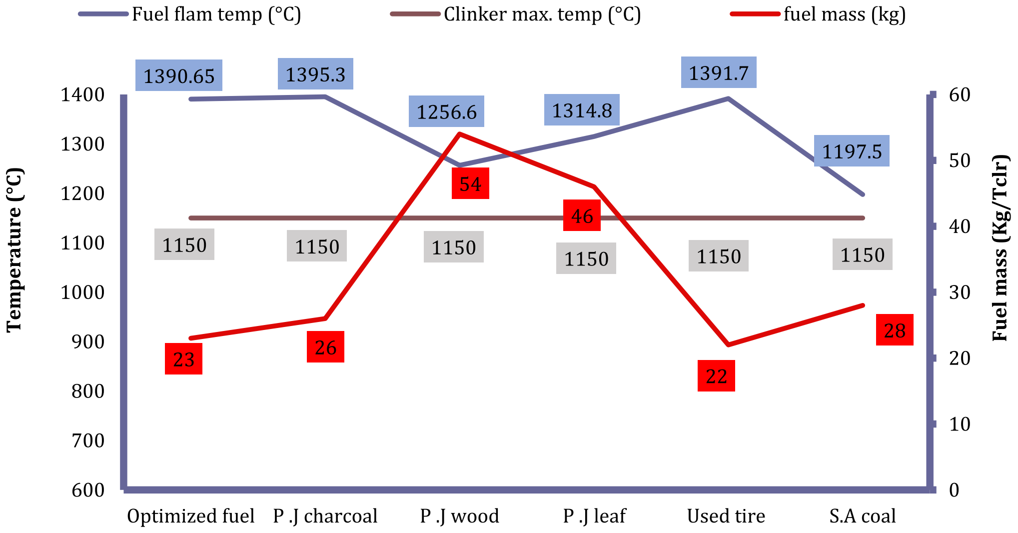

Fig. 10. Alternative fuel flame temperature compared to the South Africa coal.

Table 12
Standard for cement flue gasses emission ([1]); (EFA, 2011); (CEMBUREAU, 1999); (EC, 2001); (Zainudeen and Jeyamathan, 2008).

Emission	mg/NM^3	Kg/ton of clinker	Tons per year
NO_2	500——2000	12	400–6000
SO_2	10–3500	0.02–7	20–7000
CO_2	400–520	800–1050	0.8_*10^6 —1.04_*10^6

reduced by 17%, 21%, 9.6%, 10%, 9.1%, and 2%, respectively (see Fig. 12).

b) Sulfur dioxide

Cement manufacturing plants emit sulfur dioxide (SO2) mainly from volatile or reactive sulfur. To decrease these emissions, using low sulfur content fuel for both the pre calciner and main burner is a viable solution (Mikulčić et al., 2013). Raw materials and their processes account for over 75% of SO2 emissions while fuel combustion contributes the remaining 25% (EPA, 2011). This study examines the replacement of fuel with alternative options and analyzes the substitution of alternative fuels based on their contribution to the 25% SO2 emission resulting from fuel burning. Only 6% of the SO2 emission occurs during the burning of alternative fuels, specifically in the pre-calcining process where 40% of the 60% fuel required is used (EC, 2013) (EPA, 2011). The study found that the SO2 emissions from using alternative fuels in cement production were below the standard of 1.26 kg SO2 per ton of clinker (EPA, 2011) (CEMBUREAU, 1999). The maximum emission rate was 0.23 kg SO2 from the optimized fuel at 40% substitution as shown in Fig. 13.

Similarly, the SO2 emission from the alternative fuels was compared with the S.A coal and the result shows a huge reduction. The SO_2 emission from P. J leaf, P. J wood, P. J charcoal, used tire, and optimized decreased by 85.2%, 75.1%, 91.8%, 94.5% and 60.3% respectively at a substitution ratio of 40% as shown in Fig. 14. All proposed alternative

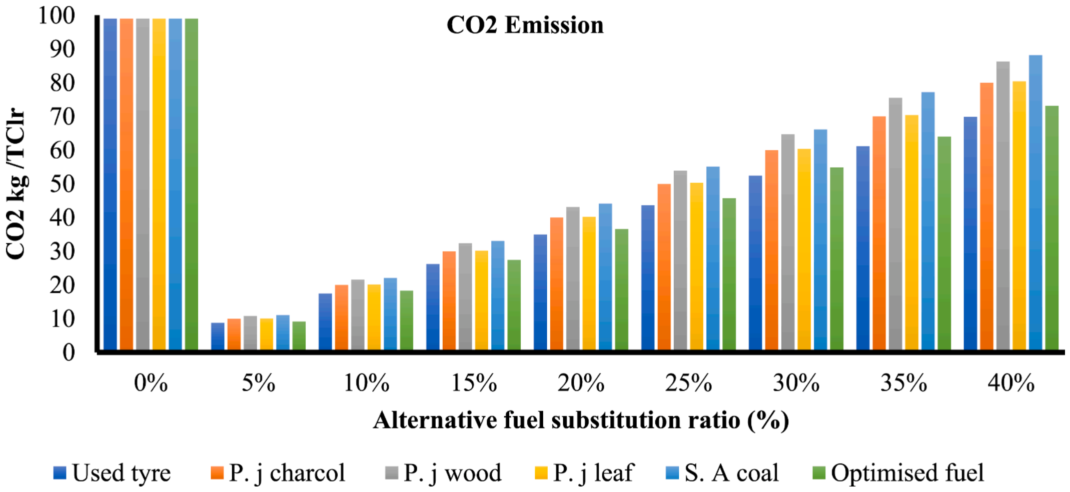

Fig. 11. CO_2 emission comparison with standards based on 40% substitution of alternative fuel in the pre calcining process.

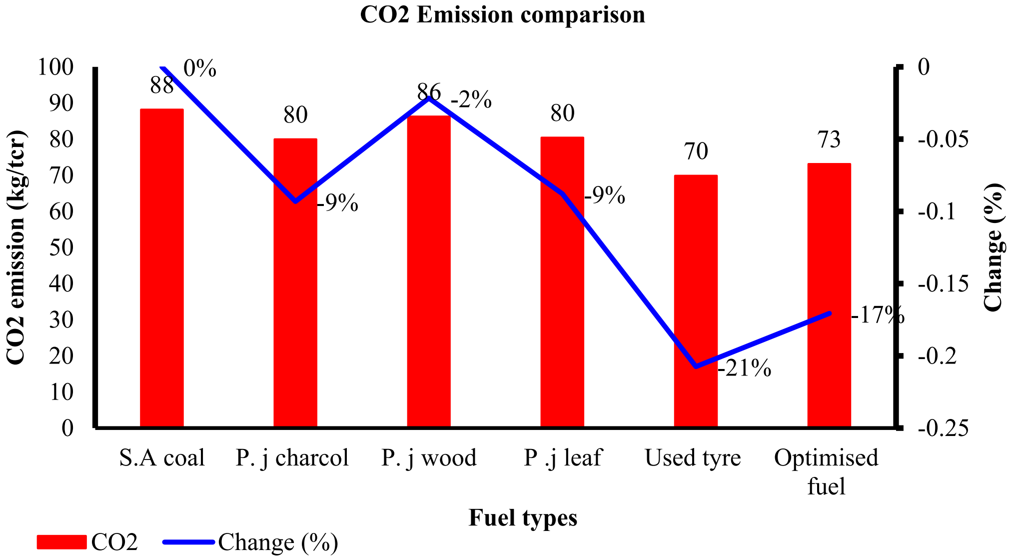

Fig. 12. CO_2 emission generation of the alternative fuels compared to S.A coal.

fuels have less amount of sulfur dioxide emission.

c) Nitrogen oxides (NOx)

Nitrogen oxide (Considered as NO_2 or (NO_X)) emission is generated in the high-temperature combustion process of clinker calcining processes in the cement kiln (Mikulčić et al., 2013). Nitrogen monoxide formation is generated in both pre-calciner and main burner in which the temperature is in the range of 1200 °C-1450 °C. The cement manufacturing industry is suitable for nitrogen dioxide formation because of its high-temperature operation process. A considerable amount of nitrogen oxide is generated from its fuel combustion as well as reactant air (Emission Standards Division, 1994) compared to the other cement production processes.

Fig. 15 shows a varying degree of NO_2 emission compared to the international standard. All the alternative fuels could be substituted up to 20% by keeping the NO_2 emission within the standard. However, the NO_2 emission from P.j wood becomes greater than the standard if the substation is greater than 20% and P.j Charcoal emits more than the standard if it is substituted at 40% ratio.

Similarly, the NO_2 emission is higher from all alternative fuels compared to the NO_2 emissions from the S.A coal as shown in Fig. 16.

Analysis of the clinker quality

The additions of alternative fuels in the cement industries have implications on the quality of cement products and the quality is characterized by alumina ratio (AR), silica ratio (SR), and Lime saturation factor (LSF). These factors are common determinants of the clinker quality in the cement production processes (Taylor, 1997) (Aldieb and Ibrahim, 2010). Globally acceptable standards of LSF, AR, and SR are shown in Table 13.

The AR factor, or the proportion of alumina to iron oxide, is the first parameter in determining the quality of cement products. The ideal range for standardized cement quality is a ratio of 1 to 4, as listed in Table 13. If the AR is lower than the standard, it creates ferrari-cement that has low heat of hydration, slow setting, and low shrinkage. If the AR is higher than the standard, it leads to faster cement setting and requires a higher gypsum rate to control it (Aldieb and Ibrahim, 2010). The analysis of alternative fuels reveals that the optimized fuel and used tire have alumina ratios (AR) of 1 and 1.982, respectively. All other fuels fall within this range, indicating that they meet the acceptable international

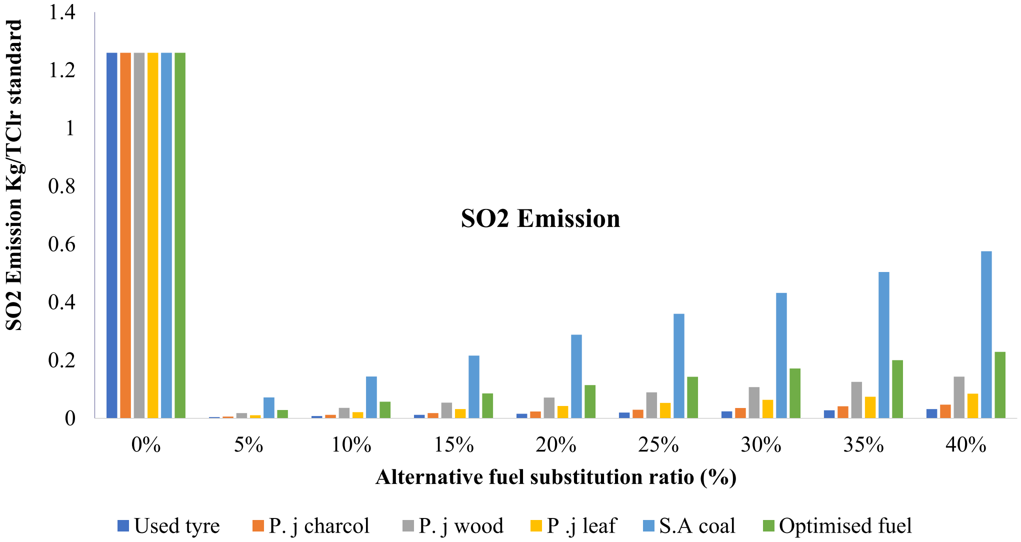

Fig. 13. SO_2 emission comparison with standards based on 40% substitution of alternative fuel in the pre calcining process.

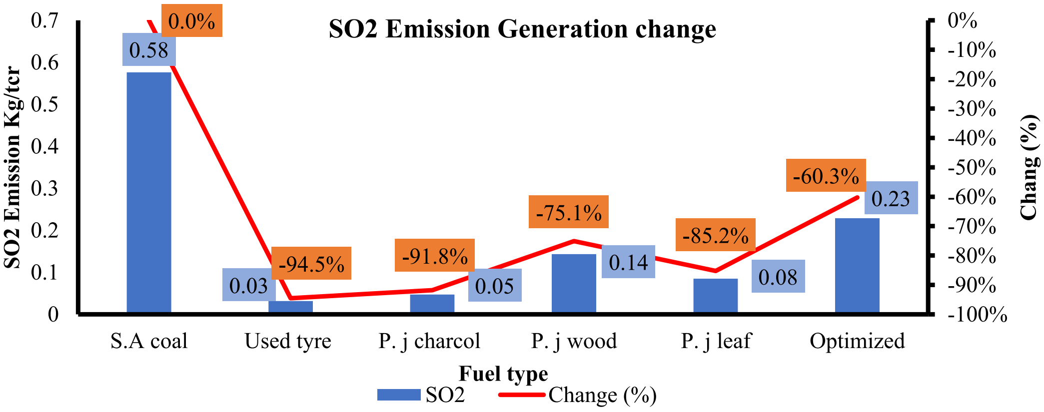

Fig. 14. SO_2 emission generation of the alternative fuels compared to S.A coal.

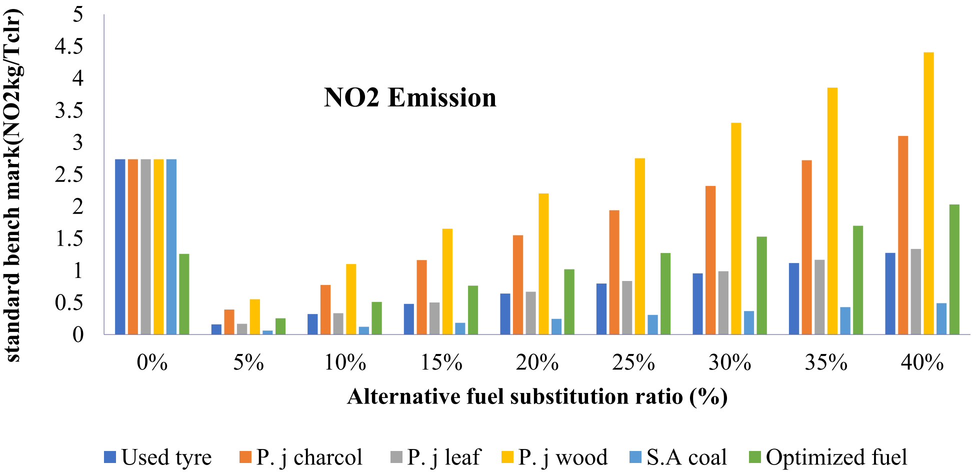

Fig. 15. NO_2 emission comparison with standards based on 40% substitution of alternative fuel in the pre calcining process.

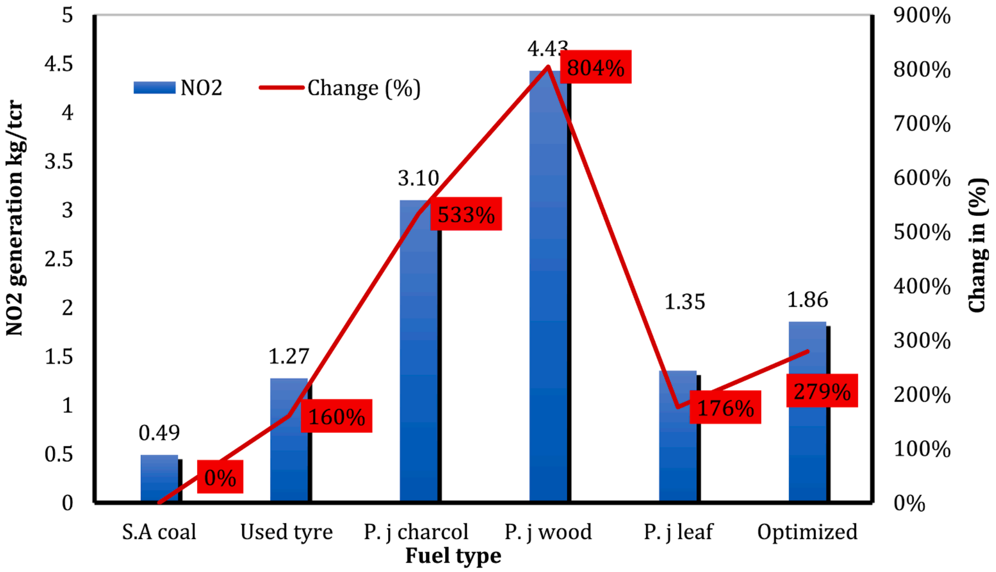

Fig. 16. NO_2 emission generation of the alternative fuels compared to S.A coal.

Table 13
SR, AR add SLF ratio factor standard for clinker production.

Factor ration type	Standard factor range	Measured values of the alternative fuels	Remark
Alumina ratio (AR)	1.0—–4.0	1–1.982	Setting property of cement
Silica ratio (SR)	2.0—–3.5	2–2.94	Control flammability of clinker
Lime saturation factor (LSF)	92—–98%	92—–93.04%	Indicate free lime amount in clinker

Sources: (Moses and Alabi, 2016).

standard for AR.

The Silica ratio (SR) is the second parameter used to evaluate cement quality when alternative fuel is used. A higher ratio affects the fuel's ability to burn and decreases cement hardness and fast setting. It also leads to kiln coating formation. Conversely, a lower SR has opposite effects. Despite this, the assessment of alternative fuels indicates that all SR values comply with international standards (see Table 13) lime saturation factor (LSF) is the third parameter that measures cement quality, indicating the amount of free lime in the clinker. This is determined by the alite to belite ratio in the clinker (Aldieb and Ibrahim, 2010) (Taylor, 1997). The lime saturation factor (LSF) of the optimized fuel is 92%, the used tire has a LSF of 93.04%, and other fuels fall in between. All analyzed fuel LSF values comply with international standards (see Table 13).

Conclusion

This study has examined and improved the use of alternative fuels made from materials available nearby (Prosopis Juliflora plant and recycled tires), which can help cement industries diversify their energy resources and reduce the cost of importing unsustainable energy. The focus was to utilize the characterized and optimized alternative fuels to replace 40% of the 60% coal consumption in the pre calcining process of the case study cement industry and to investigate its implications on emissions and quality of the cement product.

This study found that used tires can yield a high amount of calorific value. The second highest calorific value was obtained from an optimized fuel combination. All alternative fuels, except P.J bark, meet the necessary standards to be used as alternative fuels for cement industries, either individually or as an optimized fuel combination. The calorific values of different fuels were tested including P. j wood, P. j leaf, P. j charcoal, used tire, and optimized fuels. Their net calorific values were found to be between 14.37 MJ and 33 MJ per kg, meeting the minimum international standard of 14 MJ/kg. These fuels can replace up to 40% of South African coal in the clinker pre-calcining process.

By replacing 40% of existing coal, alternative fuels such as P. j wood, P. j leaf, P. j charcoal, used tires, and optimized fuels could potentially reduce CO_2 emissions by 2%, 9%, 9%, 21%, and 17% respectively. Furthermore, these alternative fuels have the potential to lower SO2 emissions by 75%, 85%, 92%, 95%, and 60% when utilizing P. j wood, P. j leaf, P. j charcoal, used tire, and optimized fuels, respectively. Unfortunately, NO_X emissions have gone up with some of the alternative fuels compared to the S.A coal being used by the case study company. But, all alternative fuels except P.j Charcoal and P.j wood meet the NO_X emission standards, with 40% coal replacement in the pre-calcining process. If P.j Charcoal and P.j wood are used, the replacements should not exceed 35% and 20%, respectively, to meet international standards.

Using alternative fuels in the cement industry affects the quality of cement, which is measured by alumina ratio (AR), silica ratio (SR), and lime saturation factor (LSF). These factors determine the quality of the clinker produced during cement production. The study found that selected alternative fuels, including optimized fuel, met international standards for AR, SR, and LSF values.

Therefore, this study confirms that using alternative fuels in Ethiopia's cement industry and other fuel-dependent countries will benefit businesses by lowering manufacturing costs, increasing competitiveness, and reducing environmental impacts caused by fossil fuels. This shows that policy makers and companies should strongly consider adopting alternative fuels to combat global warming and save money on energy costs.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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