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Co-Combustion of RDF and Biomass Mixture with Bituminous Coal: A Case Study of Clinker Production Plant in Egypt

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Abstract

Cement Clinker production in Egypt till 2013 relied mainly on fossil fuel as a primary energy source. However, with multiple fossil fuel shortages the utilization of biomass wastes was initiated by multiple cement producers. In the current work, and to present an industrial scale biomass and coal co-combustion study, the utilization of multiple biomass fuels to substitute a portion of bituminous coal was studied in an Egyptian clinker production plant. Mixtures of biomass fuels were used to reduce the consumption of the bituminous coal and to investigate diminishing the environmental impact of the clinker production process. The current study was conducted during eight days of stable clinker production process by replacing 14% of bituminous coal with biomass mixtures while monitoring the major process control parameters and resulting emissions. Emission results were compared to the nation regulations. Conclusion can be made that using biomass mixtures as alternative fuels minimized the dependency on coal as main fuel and reduced the CO_2 burden of cement production process. Additionally, NO_x and SO_2

emissions were declined while CO emissions were increased by utilizing biomass mixtures as alternative fuels; all emissions, however, were below the allowable limits stated by the Egyptian environmental authority. It was noticed that heavy elements, dioxins and furans were not changed significantly as a result of using 14% biomass fuels mixtures compared to those produced by using coal only.

1 Introduction

Cement production is an energy intensive process; where each kilogram of clinker, the main component of cement, consumes 3000 to 4000 kJ of thermal energy and up to 110 kWh of electric energy (Hosten, Fidan, 2012; Hasanbeigi et al., 2011; Chinyama, 2011). The energy consumption of cement industry represents 2% of the total world energy consumption and about 5% of the global industrial sector. The global cement industry is responsible for 5 to 10% of the total anthropogenic CO_2 (carbon dioxide) emissions worldwide (Vazquez-Rowe et al., 2018; Murray and Price, 2008; Baier, 2006; Pardo et al., 2011). The sources of CO_2 emissions are generated directly from the combustion of fuel for the formation of clinker minerals and from the decomposition of limestone where the latter holds the higher share in the emissions (Benhelal et al., 2019; Benhelal et al., 2012).

Abbreviations	
LHV	Lower Heating Value
RDF	Refuse Derived Fuel
TT	Tree Trimmings
DSS	Dried Sewage Sludge
WP	Wicker Palm
OW	Olive Waste
RH	Rice Husk
CW	Cotton Waste
PM	Particulate Matter

Cement production depends mainly on coal as energy source, however, alternative fuels such as biomass and hazardous wastes are being used in increasing utilization ratios since the 1980s (Benhelal et al., 2019; Benhelal et al., 2012; Chatziaras et al., 2013). In Europe by 2010, 10% of cement thermal energy consumption was based on alternative fuels while in the US the utilization ratio was about 11%. Biomass is one of the main alternative fuels used by cement producers globally (Chatziaras et al., 2013; Kääntee et al., 2012).

Biomass is the organic, carbon-based, material and waste that reacts with oxygen in combustion and natural metabolic processes to release heat (Basu, 2018; Brown, 2011). According to the International Energy Association (IEA) in 2011 (Madlool et al., 2011), about 3% of the cement producers around the word use biomass and its consumption attain 19% of the total energy used in some countries like India. RDF (Refuse Derived Fuel) is the main fuel used as an alternative energy source due to its abundance and sustainable stock. RDF is the result of a selective process of municipal solid wastes (MSW) which contains textiles, paper, cartoons, glass, metals, and plastics (Georgiopoulou and Lyberatos, 2017; Demirbas, 2009).

Clinker production requires the extraction of the CaO (Calcium Oxide) from limestone (CaCO3) by mixing with sand, clay and other additives and burning at 900ºC and 1500 ºC to achieve the required clinker composition (Costa et al., 2019 and Hewlett, 1998).

For utilizing the biomass fuels in clinker production there are a set of key fuel properties that regulate its use (Rahman, 2013; Mokrzyckia et al., 2003), such criteria include that the average lower heating value of the fuel should be 14 MJ/kgfuel or higher, moisture content is less than 20%, sulphur content is below 2.5%, chlorine content is below 0.2%, heavy metals contents in the fuel are less than 2500 ppm, and polychlorinated Phenyls (PCB) content is less than 50 ppm. The heating value and particle size of the biomass are the two major properties that affect the locations where the biomass fuels could be combusted as presented in Figure (1) (Chinyama, 2011; Willitsch and Sturm, 2009).

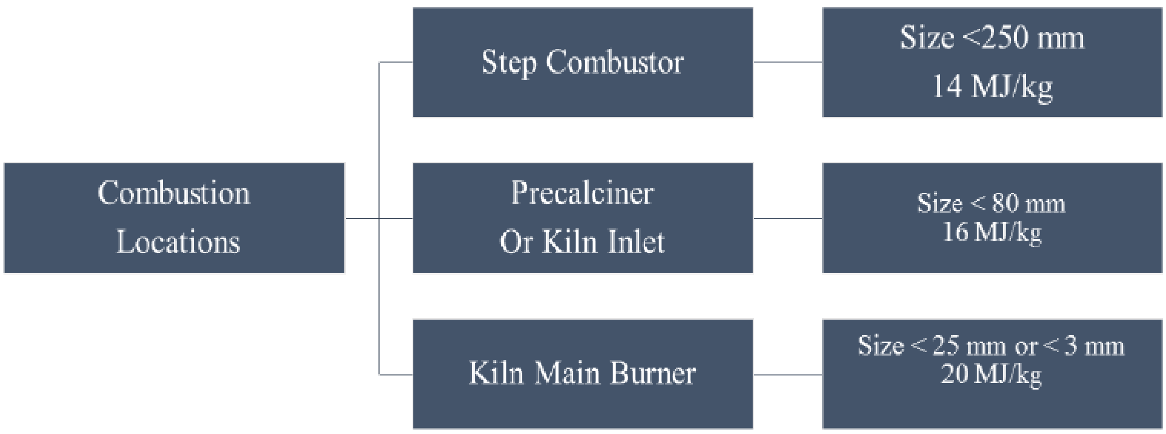

Figure 1: Possible incineration locations for alternative fuel inside cement production line based on biomass particle size and heating value (Chinyama, 2011; Willitsch and Sturm, 2009)

Biomass residues include residues from agriculture, woods, Tree Trimmings (TT), Meat and Bone Meals (MBM), sawdust, rice husks, plants residues and residues from other organic origins. Much as RDF, biomass residues need to be pre-treated, i.e., shredded, before being supplied to the combustion chamber (Chatterjee and Sui, 2019). Reza (Reza, 2013), studied a case of a cement production plant using RDF, Metro Vancouver, and concluded that the RDF tested had a lower heating value of 17.8 MJ/kg. Ash percentage was 9%.

Genon (Genon and Brizio, 2008), concluded that the substitution of coal and petcoke in the cement process with RDF enhanced the greenhouse emissions without posing substantial changes in the traditional gaseous emissions. Rovira (Rovira, 2010), studied a 15% substitution rate of petcoke with RDF. It was found that the emissions before and after the use of the RDF had similar results with respect to the concentration of dioxin and furans (PCDD/Fs) as well as the other heavy metals.

According to Chatziaras (Chatziaras et al., 2013), there was a net reduction of the carbon dioxide emissions (~ 0.4 tons CO2/ ton of coal substitution) where the moisture content of RDF was less than 15% when using in clinker production. Zhang (Zhang, 2013) reported that traditional RDF chlorine content is between 0.36% and 1.29% which limits the total substitution ratio to 54% of thermal energy.

Demirbas (Demirbas, 2009) reported that 20% substitution rate of biomass provides stable operation in the cement production process. Kara (Kara, 2012) carried out experiments on an industrial scale with substitution rates of 8%, 12% and 15% RDF with petcoke. The study concluded that the emission limits of gases NOx, SO2, CO and Particulate Matter (PM) were below the environmental directives and within the acceptable values of the industry.

Dried Sewage Sludge (DSS), which is the product of the sewage treatment plants, is also used as an alternative fuel in cement production process. Combustion of DSS in cement rotary kilns was presented as an ideal waste disposal technique according to Kijo-Kleczkowska (Kijo-Kleczkowska et al. 2016). At least three cement plants in Europe utilized 50,000 Tons annually of DSS (Benhelal et al., 2012). At substitution rates below 7%, the DSS positively impacts the final quality of clinker (Benhelal et al., 2012; Chatziaras et al., 2013).However, DSS also contains chlorine which circulates inside the process (Mokrzyckia et al., 2003).

Uson (Uson, 2013) found that the use of biomass residues such as Rice Husk (RH) and Woody Biomass residues produced lower NOx and SO2 emissions. This was explained by their nitrogen and sulphur contents were lower than traditional coal and petcoke fuels.

The formation of dioxins and furans from the chlorine content of the biomass combustion represents a major concern. However, dioxins emissions were not frequently increased drastically during the cement production process by using alternative fuel (Richards and Agranovski, 2016). Such data were supported by Court (Court, 2005) and Rahman (Rahman, 2013).

Locally, the energy intensive industries in Egypt consume 51% of the local energy generated. Cement represents 59% of such share. The industries of cement, refractory and fertilizer are responsible for 32.8 Million tons of the CO2 emissions which represents 16.25% of the total CO2 emissions in 2016.

The cement production sector in Egypt relied mainly on natural gas and oil. On one hand, multiple shortages since 2013 in natural gas supply for energy intensive industries such as cement manufacturing led the substitution of natural gas with coal and alternative fuel sources. While on the other hand, agricultural, industrial and municipal wastes in Egypt whose potential is 40-60 million tons per year represented a major concern since 85% are open dumped and landfilled (Al-Karaghouli, 2007). Such potential had an increasing share in cement industry since then although no national plans were set to utilize such potential (Radwan, 2012; Ionita et al., 2013).

Therefore, in the present work, utilization of multiple biomass fuels was studied on an industrial scale clinker production plant. The used biomass fuels were non-hazardous as well as not required special environmental permits. The biomass fuels were not fed individually into the combustion chamber but mixed together. The mixtures of the biomass fuels targeted to reduce the consumption of the bituminous coal and to diminish the emission of the clinker production process. Such values were compared to those stated in the Egyptian environmental regulations. The novelty of the present work is to provide an industrial scale application for co-combustion of RDF with bituminous coal. The lack of data and resources on the quality of biomass fuels available in Egypt and the lack of information on their utilization presents a major corner stone in the present work. Moreover, the proposal of mixing RDF with biomass fuels poses a potential for producing enhance properties of alternative fuel rather than relying on a single fuel which can negatively affects the co-combustion process.

2 Materials and Methods

2.1 Case Study Plant

The present study discusses an Egyptian cement plant with a productivity of 6000 clinker tons per day. The plant has two identical production lines working with dry powder process, with 5-stage cyclone preheater and precalciner in each line. The biomass fuels utilized are derived wastes from municipal, agricultural, and industrial sources without hazardous elements since such fuels were not requiring additional environmental permits. The thermal energy was consumed inside the precalciner, which is a 40m long stationary cylindrical combustion chamber, holds a share of 65% of the fuel consumption. The temperature inside the precalciner is around 900ºC at which decomposition of limestone takes place. The remaining 35% of thermal energy was consumed in the rotary kiln, which is 78m long and 5m in diameter, in which the ambient temperature is 1450ºC. The kiln burner is a multi-channel burner for burning solid, liquid and gaseous fuels. The combustion of coal and alternative fuel in the precalciner relies on auto-ignition of fuel without burners.

The chlorine content in the raw material in Egypt is generally high. Hence, bleeding and disposing a portion of the gases and clinker material is needed so that chlorine content in the process could be decreased. The bleeding system depends on the extraction of the kiln hot gases with kiln clinker dust of high alkali content to prevent build up in the kiln and preheater internal walls. In this case study plant, the bleeding was normally at 10-13% ratio of kiln hot gases due to the high chlorine content in the raw material feed. Such content limited high rates of substitution of coal with chlorine containing fuels such as RDF with shredded plastic bags. The operational parameter limit in the case study plant for bleeding was 15% of kiln gases which limited a complete utilization of RDF as alternative of coal.

The heat required for the study clinker production process was realized by feeding the fuels in two locations: The bituminous coal was burnt inside the rotary kiln while a mix of the bituminous coal and the biomass fuels was used inside the precalciner. Feeding alternative fuel in the kiln main burner required finely shredded RDF with lower heating values above 20 MJ/kg_{fuel}. Such values weren't attainable in the RDF fuel samples tested during the early design process of the RDF combustion system as well as the need for multiple shredding system rather than using a single shredder as in the case study. While some cement manufacturers prefer to incinerate the alternative fuel as received without pre-treatment, in the current study, the alternative fuels are being pre-treated by using magnetic separation to remove metals and pre-shredded to 50mm before feeding into the combustion chamber. Additionally, combustion at substitution ratios above 20% represented a technical challenge in terms of stable operation and availability of air draft fan with enough capacity to transport the increased volume of gases and dust load. The cost related to upgrading the precalciner to allow longer retention time of RDF for complete combustion was limited and hence such obstacles limited increasing the feed rate of RDF and biomass blend.

The fuels used in the precalciner in the present case study was composed of 86% bituminous coal and 14 % biomass fuels based on thermal energy share. The control process of the air and fuel flow was based on the temperature inside the precalciner chamber. The set point of 870ºC was maintained through the variation of the fuel feeds. The biomass mixture weigh feeder was controlled by a load cell suspended on a spring to indicate the feeding rate of the fuel to the precalciner. Any drop in the temperature inside the precalciner due to a lower heat biomass value for the mix (LHV) or a high moisture content will automatically increase the coal weigh feeders flow to maintain the set point. A tertiary air damper tongue preceded the tertiary air duct. It was mechanically adjusted to manipulate the air flow from the cooler to the precalciner. The temperature inside the precalciner was measured using a K-Type thermocouple placed above the combustion section while the tonnage of both coal and biomass fuels were controlled by load cell sensing weigh feeders.

2.2 Measuring Techniques and Control

The alternative fuels used in the present study were analysed as received from the suppliers and after its size reduction inside a mechanical shredder before feeding for combustion. The samples collected from the solid fuels were tested according to EN 15415-1:2011 Standard.

The rate of sampling technique for the RDF and biomass could be adjusted according to the operational parameters requirements. For example, if there was a surge in the CO emission value at the precalciner exhaust gases, the particle size of the shredder output must be tested in shorter time intervals to ensure enough burnout time inside the chamber. The sieve apparatus for the biomass fuels were recommended to be those of 80, 50 and 25 mm size. The sieves were stacked vertically and were stirred mechanically.

Another example for adjusting sampling periods was the rise in sulphur dioxide emission was usually attributed to the coal, the correction in this case requires changing, the pile feeding of the mill and hence no change in the feeding of RDF was required. However, if the changing the coal feed to the precalciner then an action towards the alternative fuel was made. If more parameters were changed during the operation, it was recommended to collect more samples to ensure stable operation.

There were three gas analysers installed on the process line located at the kiln gases exit to the preheater tower, at the chlorine bleeding system and at the preheater gases upper level. Such analysers could be used to exhibit all gases concentrations within the process gases flow like O_2, CO, CH_4, CO_2, NO, SO_2, CO and NO_x were displayed in % volume of the gases or in ppm according to its initial setting. The types used in the case study was Single Dried Water Cooled Probe (SDWP KilnLoq) Gas Analyser operating at maximum process temperature of 1200 ^{O}C and a maximum dust concentration of gas sample extracted to be 500 gram dust/m^3 of gas. All gas samples were analyzed by online gas analyser that's in continuous operation with the process line and their online output was seen on the operator's screen.

The concentration of dust in the stacks for environmental online monitoring was performed by an online dust concentration meter of the type DURAG 300. The DURAG 300 follows the standard DIN EN 15267-3 with a minimum detection limit of 0.01 mg/m^3.

2.3 Characterization of Biomass

The main fuel used for combustion in the precalciner of the clinker production line was RDF. However, the variation in the RDF properties due to different sources of supplies presented multiple operational obstacles in terms of moisture and chlorine content in addition to the variation in the fuel heating value. The variations were represented in moisture content values between 7.3 and 35.2%, chlorine content between 0.04 and 1.32%, ash content up to 25.6% and lower heating values changed from 8 to 19 MJ/kg_{fuel}. Such variations were realized by mixing the RDF with other sourced fuels from the local market. After multiple trials with different percentages, it was realized that a fuel mixtures consisted of 80% RDF as a basic fuel shredded to 50-70 mm and the rest as 20% was composed of two or three types of wastes according to the time of supply such as tree trimmings (TT), Dried Sewage Sludge (DSS), wicker palm (WP), olive wastes (OW), rice husk (RH) and/or cotton wastes (CW). The densities of the delivered biomass fuels were found between 150 and 200 kg/m^3. As shown in Table (1) the fuels fed during eight days of stable operation while their elemental analysis of both RDF and the mixtures as illustrated in Table (2).

Table 1: Mixture of fuels during eight days of continuous stable operation

Date	Fuel mixture tested	Feed Duration per day (hours)
15-Mar-2015	RDF+TT+RH	24
16-Mar-2015	RDF+TT+OW	24
17-Mar-2015	RDF+TT+DSS	24
18-Mar-2015	RDF+TT+WP	24
19-Mar-2015	RDF+TT+CW	24
20-Mar-2015	RDF+TT+RH	24
21-Mar-2015	RDF+TT+ DSS+CW	24
22-Mar-2015	RDF+TT+CW+WP	24

Table 2: Ultimate analysis on dry basis of the fuels tested (During the eight days of test)

Element	RDF*	15-3	16-3	17-3	18-3	19-3	20-3	21-3	22-3
C [wt.%]	56.9	57.50	59.46	51.30	53.40	52.05	57.80	54.93	60.40
H [wt.%]	6.1	8.05	7.47	8.20	8.63	8.59	7.90	6.95	6.06
N [wt.%]	1.1	1.60	3.03	1.92	2.20	2.73	1.80	2.05	7.08
O [wt.%]	34.8	31.40	29.42	37.71	35.00	31.20	35.53	25.90	26.4
S [wt.%]	0.2	0.55	0.12	0.17	0.27	0.30	0.40	0.24	0.36
LHV [MJ/kg] **	14.0	13.70	13.84	12.90	14.60	14.00	14.72	15.10	15.13
Ash [wt.%] **	19.9	19	18.17	14.7	20.21	16.92	18.30	19.53	15.67
H_2O [wt.%] **	21.7	17.45	19.94	22.4	17.3	18.32	18.8	18.87	20.03

*RDF tested before mixing, the single value is due to using one single source of RDF supply
**LHV, Ash and H_2O are tested separately since volatile matter content couldn't be tested during the experimental work

3 Results and Discussion

The environmental impact of using different mixtures of biomass as alternative fuels for substitution of bituminous coal with share of 14% of the total heat consumption was investigated over a period of eight consecutive days in March 2015. The days were selected based on the continuous non-stop operation of the production line. That's attributed to the limit the process and emissions variations that would alter the findings give non indicative results. Moreover, stack emissions would be changed while using natural gas or diesel during emergency start-up or shutdown which manipulates the gases emitted and hence could provide non indicative results.

During the eight day test period, the daily average values of PM (Particulate Matter), NO_x, SO_2 and CO were monitored and compared to those stated by the Egyptian Environmental Law No. 1095 for the year of 2011. As for the heavy elements and dioxin emissions, the measurements were taken by collecting samples from the main exhaust gases stack for a period between 6 to 8 hours at the last day of the measurements as per environmental regulation. The emissions registered while using the different mixtures of biomass with coal were compared to those resulted from the operation with pure bituminous coal in the second production line during the same period. Both production lines are identical in terms of process equipment and operation where such comparison can present a prospect of the impact of utilization of RDF and its mixtures. Figure (2), (3), (4) and (5) present the average daily emissions in mg/Nm^3 for Particulate Matter, NO_x, CO and SO_2 respectively. Solid lines represent emissions from the second operation line used bituminous coal as a single fuel source, and the dash lines represent the operation line used RDF/Biomass blend.

As for the resulting emissions and as shown in Figure (2), the particulates emissions in the case of using the biomass mixtures blended with coal showed the lowest average value compared to those resulted in the case of using coal. This could be attributed to higher air to fuel ratio needed in the case of coal combustion was attributed to having a higher particulate matter emissions since more air was supplied to the process. However it is difficult to differentiate the unburnt hydrocarbon of the coal fuel and the raw material dust particles since both have similar particle size. Also, it could be elucidated due to the higher oxygen contents of the alternative fuels. The highest value obtained was on the third day of the test with 35.8 mg/Nm^3 which is lower than the limit of 50 mg/Nm^3. The values are found according to the normalized condition of 10% O_2 content in the exhaust gases to ensure that no dilution of the gases took place to alter the findings. The device used in such measurement is a dust concentration meter (DURAG 300) which measures the opaqueness of material in the exhaust gases.

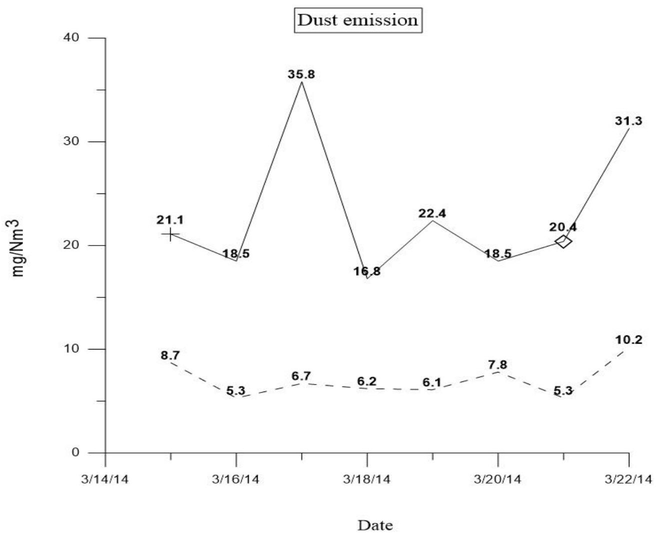

Figure 2: PM emissions over 8 days in March 2015. (Solid line: bituminous coal, dash line: biomass-Coal blend)

The values of the PM produced due to the combustion of biomass/coal blend when compared to the bituminous coal combustion in the second line indicate that depending on the RDF/Biomass mixture with coal for combustion has a positive impact on dust emissions since the values highest value attained was 10.2 mg/Nm^3. However, the availability of imported coal and the abundance of biomass based fuels is a corner stone in this study since the continuous supply and optimization of the RDF/Biomass mixture faced numerous obstacle due to the variation in each supplied fuel properties.

The highest values obtained for NO_x emissions were found to be equal to 516 mg/Nm^3 for the case of operating with bituminous coal as a primary fuel source as illustrated in Figure(3). In case of using biomass mixtures blended with coal the NO_x emission was lowered and attained a value of 364.73 mg/Nm^3. Such case could be explained by Uson (Uson, 2013) where the use of biomass residues produced lower NO_x emission since its nitrogen content was lower than the traditional coal and petcoke fuels. Additionally, the release of nitrogen in the case of alternative fuel was in the form of ammonia (NH_3) which acts as a reduction agent for NO_x. The NO_x emissions were analyzed using SDWP (Single Dried Water cooler Probe Kilnloq) device.

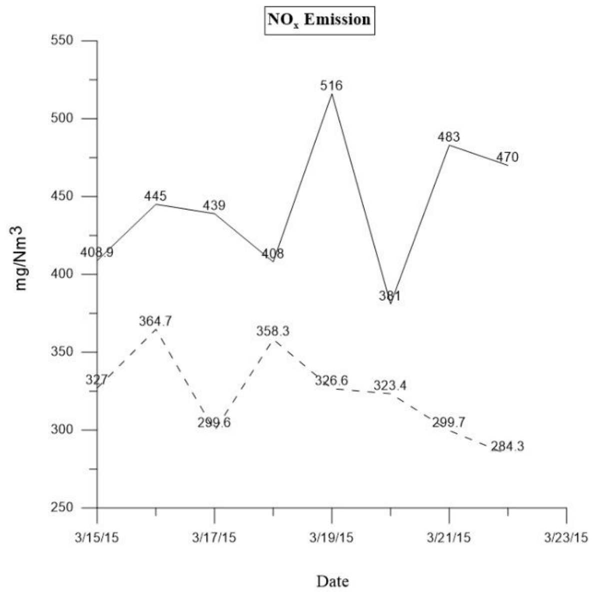

Figure 3: NO_x emissions over 8 days in March 2015. (Solid line: bituminous coal, dash line: biomass/coal blend)

The highest NO_x emissions unlike PM were depicted from the combustion of bituminous coal solely. Compared to the environmental limit of 600 mg/Nm^3, the combustion of coal clearly indicates that violating the limit is a likely result during kiln operation. The positive impact of using a mixture of biomass/coal contributed to lowering the values of NO_x emissions almost to 50% of their original values.

The CO emitted in the present study acts as a reducing agent for the NO_x formation. Thus the biomass mixtures blended with coal were found to generate higher CO as 48.4 mg/Nm^3 as shown in Figure (4). In case of coal utilization the CO as 3.4 mg/Nm^3 was lower than that in biomass blended with coal and agreed with the findings of Kara (Kara, 2012) as well. This behaviour is explained by incomplete combustion of the biomass mixtures blended with coal due to moisture contents of such alternative fuel. Additionally, the available burnout time required for biomass fuels inside the precalciner is around 6 to 8 seconds which doesn't allow a complete burnout process even with cases of lower moisture content. The violation limit for CO emission is 250 mg/Nm^3 and the highest attained value from the biomass/coal blend remains well beyond the inacceptable range.

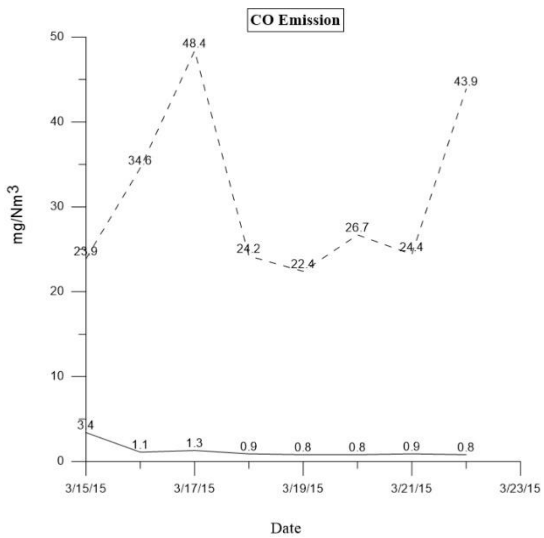

Figure 4: CO emissions over 8 days in March 2015. (Solid line: bituminous coal, dash line: biomass/coal blend)

Regarding the sulphur dioxide emissions and as shown in Figure (5), the levels of SO_2 emissions were highest in case of using coal as a single fuel source than those in the case of using blends of biomass with coal but, all the levels were below the Egyptian Environmental limits. It could be found that utilizing coal as a single fuel for combustion produced higher SO_2 emissions whereas the highest value detected was identified as 11.9

mg/Nm^3 compared to 5.1 mg/Nm^3 which is almost 50% lower when using biomass/coal mixture. Compared to the 250 mg/Nm^3 environmental limit, the highest value detected remains at almost 10% of the violation limit which doesn't pose an environmental risk. SO_2 emission levels presented the best performance of gaseous emissions in the present study. It could be attributed to the content of sulphur in the raw coal feed alone that higher SO_2 could be found in the coal operation against the biomass/coal blend.

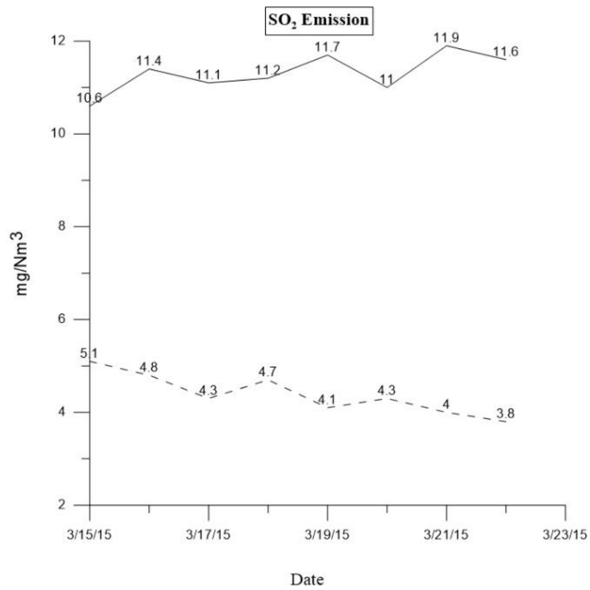

Figure 5: SO2 emissions over 8 days in March 2015. (Solid line: bituminous coal, dash line: biomass/coal blend)

As for the assessment of heavy elements and their emissions, it is worth to mention that the presence of hydrogen fluoride and hydrogen chlorides doesn't impact negatively the emissions since the clinker production atmosphere was alkaline. This was supported by the results illustrated in Table (3) where the concentrations of these two compounds were reduced with the use of the biomass mixed with bituminous coal from 0.052 to 0.04 and from 8.02 to 7.07 mg/Nm^3 respectively. The compliance of these levels with the permissible Egyptian environmental requirements was met, however, closer observation should be considered.

The reduction in the total heavy metals concentrations in the exhaust gases agreed with Genon (Genon and Brizio, 2008). There was no proof, however, that the concentrations of mercury (Hg) and lead (Pb) increased with the substitution of the primary fuel by RDF.

Table 3: Heavy elements emissions at 14% substitution with biomass fuels mix

Pollution Element	Unit	Coal with Biomass	Coal	Egyptian Limit
Total Organic Carbon (TOC)	mg/Nm^3	1.2	1	10
Hydrogen Chloride (HCl)	mg/Nm^3	7.07	8.2	10
Hydrogen Fluoride (HF)	mg/Nm^3	0.04	0.052	1
Lead (Pb)	mg/Nm^3	0.014	0.01	2
Mercury (Hg)	mg/Nm^3	0.017	0.013	0.05
Total Heavy Elements	mg/Nm^3	1.52	1.9	2.5
Dioxins and Furans	ng/Nm^3	0.032	0.031	0.1
O_2 of gases at stack	[%vol.	10.1	10.3	10
Temperature of gases at stack	[^{o}C]	119	116	115-120

The table indicates that the TOC (Total Organic Carbon) values increased by 0.2% when using the alternative fuels with coal compared to using coal as a single fuel source. This is attributed to the organic nature of the alternative fuel which normally lead to increase in such values.

Nonetheless, the major concern of combustion of was the formation of dioxins and furans due to the chlorine content especially presented in the RDF. It is worth to mention that the emission limits of the European and the Egyptian standard specifications is 0.1 Nano gram/m^3. The formation of dioxins requires the existence of either chlorine in the combustion process (from Raw Materials and/or Fuels) or carbon or similar organic precursor with gas temperature between 200 and 450^{o}C. Also, such formation requires the existence of a catalyst such as copper, iron in the process with a surface which enables the catalyst to drive the generation of the dioxins. Thus, to prevent the formation of dioxins a rapid cooling of the gases is needed to keep the gases temperature below 200° C or by using gas cleaning and capturing equipment such as bag filters and electrostatic precipitators.

The bag filters and the electrostatic precipitators (EP) were main assets in any cement plant. Each cement production line contains around three electrostatic precipitators located before the stacks of the cooler, the bypass and the main stack. Inside the bypass and the main stack EP filters there were two water cooling towers for spraying water on the hot gases to cool them rapidly below 200° C (150° to 100° C) before exhausting from the stacks. It also reduces the thermal stress on the filter internal parts at such high temperatures. Hence it can be stated that the requirements needed to prevented the formation of large amounts of dioxins and keep the emissions levels under the Egyptian environmental limits can be found in a typical cement clinker production plant.

Conclusion

The following conclusions were summarized from this work as:

As one of the major consumers for traditional energy in Africa, Egyptian clinker production industry suffered from energy shortages which affected all cement manufacturers. One approach for solving such issue was the utilization of alternative energy sources. The presented case study can be considered as one of the industrial scale applications for waste energy utilization. The case study where RDF and biomass wastes were used to replace 14% of bituminous coal for clinker production presented an optimistic projection for waste management as well as positive environmental output. It can be stated that the usage of biomass as secondary solid fuel in the cement manufacturing was successful and added value for solid wastes management. The RDF and biomass mixtures could substitute only 14% of heat energy needed in cement industry due to high chlorine content which causes increase in gases bleeding from the process. Although the chlorine content of RDF wasn't the main precursor for the bleeding process, nonetheless it contributed to 2 to 3% increase in bleeding rate of gases. Increasing the RDF rate can be achieved based on lower chlorine content found in clinker constituents.

As for CO_2 emissions, using the biomass fuel mixtures which can be considered as CO_2 neutral, has the advantage of minimizing the dependency on coal as a source of fuel and to reduce the CO_2 burden of cement production. Such assumption was adopted initially by (Georgiopoulou and Lyberatos, 2017) and (Uson, 2013). However, the CO_2 footprint related to the transportation and addition of RDF and biomass fuels can be of little impact since the saving in bituminous coal combustion can be a benefit which balances to some extent the RDF CO_2 footprint.

The mixing of the different types of biomass fuels was advantageous compared to using RDF solely as it provided better fuel characteristics through lowering the ash, moisture and chlorine content. Such practice can be considered as a key solution to future research as well as practical applications since not many research papers or case studies discusses in details the analysis and types of biomass fuels which can be used with RDF to improve the RDF properties. While RDF remains the available fuel due to its abundant stock but mixing with biomass residues does enhance the fuel properties. The variation in moisture and chlorine content of DSS, Olive wastes and other biomass waste fuels must be thoroughly characterized before mixing. All biomass residues represented a positive impact on the final alternative fuel mixture. Similar applications in other countries other than Egypt require thorough investigation and characterization of alternative fuels before mixing and feeding for combustion. Hence, all biomass wastes can be considered as alternative fuel sources for cement clinker production process. RDF and biomass waste fuels can substitute coal with minimal effect on both process and environmental impact and in some cases, the environmental impact of coal combustion can be diminished using such alternative fuels.

In terms of gaseous emissions, NO_x and SO_2 emissions were found to be depressed while CO values increased with the use of biomass mixture; all values were, however, below the Egyptian environmental limits.

Moreover, the use of biomass/coal mix did not influence on the emissions of heavy elements, dioxins and furans and all the values were below the Egyptian environmental limits. In terms of produced clinker, no variation could be detected in the clinker quality due to the use of RDF and biomass fuels. However, with increasing substitution ratio, such finding can change and hence continuous monitoring is needed. A complete energy balance would represent a major research point which can follow the current research and will provide a thorough investigation of the decomposition of RDF and biomass fuels.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests

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Authors' contributions

OA and MN performed the experiments, the analysing the results and writing the manuscript. KI and JY contributed to the assessment of the results and conclusion. All authors read and approved the final manuscript.

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