Chapter

Sustainable Solid Waste Management in Morocco: Co-Incineration of RDF as an Alternative Fuel in Cement Kilns

Aziz Hasib, Abdellah Ouigmane, Otmane Boudouch, Reda Elkacmi, Mustapha Bouzaid and Mohamed Berkani

Abstract

The management of municipal solid waste (MSW) is a major obstacle for the majority of municipalities in developing countries because of the impacts related to the landfilling of waste. Garbage is an energy-rich material. As a result, energy recovery is considered to be a sustainable waste management method. In Morocco, 7.4 million tons are produced annually; most of the waste is landfilled without any recovery despite the impacts related to this method of disposal. The objective of this chapter is to characterize combustible fractions (RDF) from household waste in Morocco and to study the economic and environmental benefits of their use as alternative fuels in cement kilns. The results of this research show that the combustible fractions contained in household waste in Morocco constitute a potential sustainable energy source with a high lower calorific value (4454 kcal/kg). The study of the advantages of co-incineration shows that the substitution of pet coke by 15% RDF reduces the pollution linked to gaseous emissions. In addition, the cement plant can make financial savings 389 USD/h by minimizing the use of fossil fuels.

Keywords: municipal solid waste, energy recovery, RDF, cement plant, Morocco

1. Introduction

With population growth and improved living standards, the generation of household waste continues to increase throughout the world [1, 2]. Despite its health and environmental impacts, landfilling remains the most common method of waste disposal in developing countries [3, 4]. Several treatments can be used to recover the material and energy contained in the waste. The main energy recovery methods that can be used are incineration, pyrolysis, gasification, bio-methanation and RDF production [5]. The choice of treatment method depends on the qualitative and quantitative characteristics of the waste. A study conducted by Ouigmane et al. [6], showed that household waste in Morocco is a potential source of combustible fractions [6]. These fractions are the basic element of RDF production. Indeed, studies have been carried out in developed countries related to the use of RDF in cement kilns as an alternative fuel for petroleum coke have shown several economic and environmental advantages of this line of recovery [7–18].

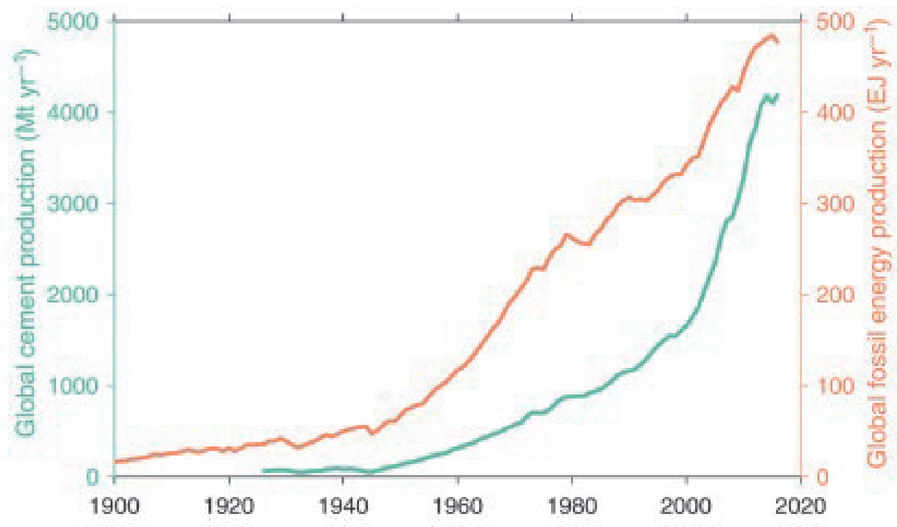

Figure 1.
World cement and fossil energy production until 2016 [21, 22].

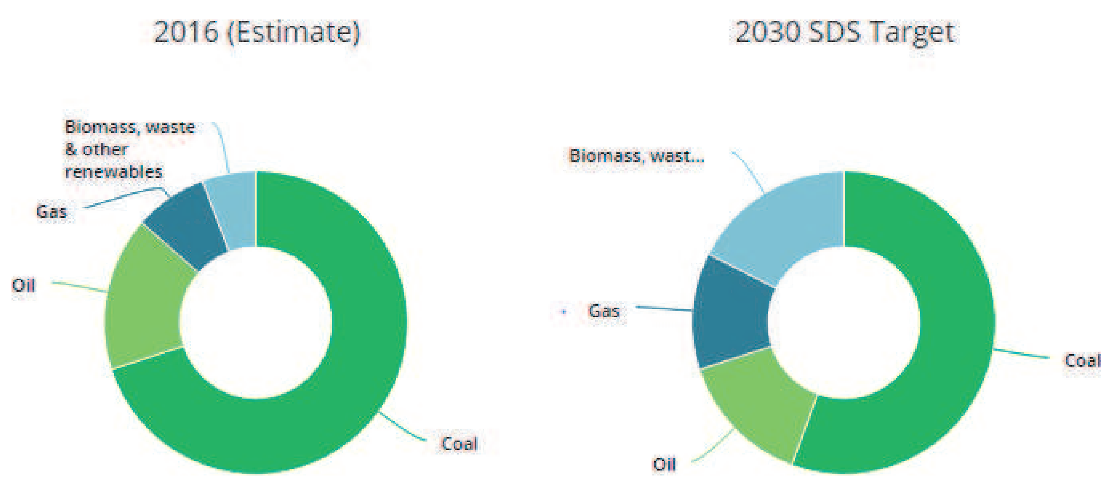

Figure 2.
Overall thermal energy consumption for cement production by fuel [25].

The cement sector is a major energy consumer [19], a simple change in the management of energy consuming sources can have a positive effect on the plant's energy consumption [20]. Indeed, the cement sector is largely linked to the consumption of fossil fuels (**Figure 1**) [21, 22].

Improving the energy efficiency of energy-intensive industries (e.g. cement plants) will contribute significantly to improving their economic competitiveness in the global market [23, 24]. In order to improve their image, cement plants are trying to replace petroleum coke, which is a polluting fossil fuel, with less polluting alternatives such as RDF or renewable energies. To achieve the 2030 sustainable development goals, the share of fossil fuels must decrease as shown in **Figure 2** [25].

The objective of this chapter is to assess the economic and environmental benefits of using RDF as a substitute for fossil fuels in a cement plant for a region in Morocco.

2. Waste management in Morocco

2.1 Legislative framework for waste management in Morocco

The management of municipal solid waste (MSW) requires knowledge of the legal and institutional contexts that concern this sector. In Morocco, the main problem of the MSW management sector is manifested in the legal and institutional context, in particular the weakness of the means available to the competent local authorities in terms of solid sanitation and the inadequacy of legal and regulatory texts. Despite all these problems, Morocco has made several efforts and launched Law 28-00 on waste management in 2006 and the national plan for household waste management. Thus, the new Organic Law of Territorial Communes 113-14 relating to communal organization, specifies in its Article 83 that solid sanitation, household waste collection and waste treatment fall within the competence of the communities [26].

2.2 The production of household waste in Morocco

The production of waste in Morocco, as in the rest of the world, does not stop increasing due to the intervention of several factors (population, standard of living, urbanism etc.). The waste production rate in urban areas is 0.76 kg per capita per day and 0.28–0.3 kg per capita per day in rural areas [6–28]. Waste production varies from one region to another, in the region of Rabat the production ratio is 0.96 kg per capita per day [29] and in the city of Beni Mellal the rate is 0.89 kg per capita per day [30].

2.3 The composition of household waste in Morocco

The qualitative aspect of waste is a key parameter in the choice of treatment method. The general composition of waste in Morocco is characterized by a high content of biodegradable material with a percentage that varies according to urban and rural areas and decreases over time as a result of the improvement in living standards. The average composition of MSW in Morocco is shown in **Figure 3** [28].

2.4 Waste disposal in Morocco

Prior to the implementation of the National Plan for Household Waste, almost all of the waste generated in Morocco is disposed of in uncontrolled landfills without any control. The country has become increasingly sensitive to the impacts of uncontrolled dumping and the costs of environmental degradation that can result. As a result, the Ministry of the Environment has launched the National Plan for Household Waste to rehabilitate all uncontrolled landfills and replace them with controlled landfills or landfill and recovery centers (LRC) with a 20% recovery by 2022.

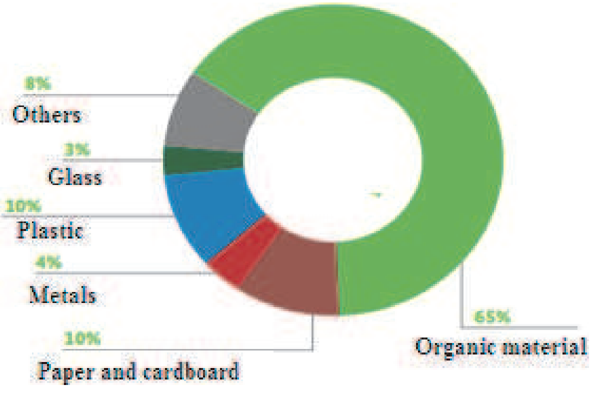

Figure 3.
Average composition of household waste in Morocco [28].

Municipal solid waste	Average cost (Million MAD)
Dommage	
Cost of non-coverage of the population by collection	1118
Cost of groundwater pollution	195
Depreciation of land in the vicinity of landfills/disposal sites	19
Loss of opportunity	
Lost electricity potential	848
Lost recycling potential	204
Total in Million MAD	**2384**
% GDP	**0.26**

Table 1.
Costs related to environmental degradation by the waste sector [31].

2.5 The cost of environmental degradation through waste management in Morocco

Environmental deterioration is not limited to damage to health and ecosystems, but can affect a country's economy. Morocco's efforts in recent years have led to an improvement in the situation of the environmental sector, which is proven by the results of the studies of the cost of environmental degradation in Morocco in 2000 and 2014. These studies are carried out by the World Bank and have shown a 20% reduction in this cost in 14 years. Indeed, the cost of environmental degradation has gone from 590 MAD per inhabitant in 2000 to 450 MAD per inhabitant in 2014 [31]. The costs of environmental degradation related to waste management are presented in **Table 1** [31].

3. Cement sector in Morocco

3.1 Data on the cement sector in Morocco

Cement is one of the oldest industries developed in Morocco, with a first plant in Casablanca at the beginning of the 20th century. Today, the activity is structured and covers the whole territory. The Moroccan cement sector is made up of four companies that operate a total of 12 production plants distributed throughout the country (**Figure 4**) with an annual production capacity of almost 21 million tons [32]. All the plants benefit from modern technologies and an efficient management system. In addition, the professionalism and expertise of the staff and the support of three of the world's largest cement groups guarantee product quality.

The development of the cement industry is linked to the economic development of the country and the upgrading of the construction and housing sectors. In 2011, cement consumption peaked at 16 million tons. Since 2012, the construction materials market has been in decline, mainly due to the drop in construction activity [32].

4. Case study

The objective of this part is to make a case study on a region in Morocco in order to assess the economic and environmental benefits of the co-incineration of RDF in a cement kiln.

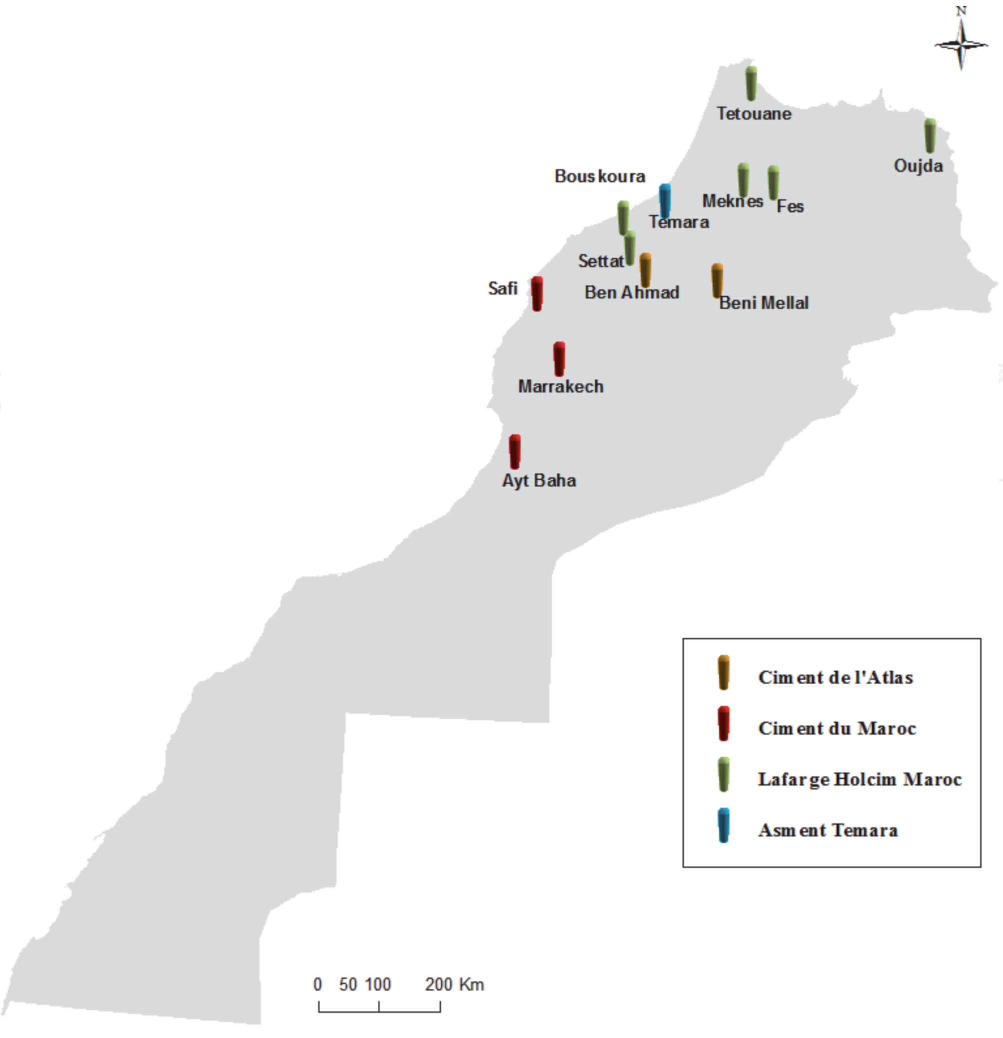

Figure 4.
Distribution of cement production plants in Morocco.

4.1 Materials and method

4.1.1 Waste management in the study area

The province of Khenifra is located in the center of Morocco and is made up of 22 communities (**Figure 5**) with an estimated population of 379,639 inhabitants in 2019 [33]. The management of household waste is a major obstacle for the territorial communes, especially in the disposal phase. Since 2017, an evolution in the mode of waste management in the province of Khenifra has been noticed, with the organization of burial by changing the mode of uncontrolled dumping to a mode of controlled landfill. Despite the efforts made by the communities and the Ministry of the Environment, current waste management is encountering problems and does not meet expectations, since the energy and matter contained in the waste is lost underground. In addition, the controlled landfill is poorly located, as its geographical location can cause several impacts on health and the environment (**Figure 5**). Therefore, it is necessary to look for sustainable and cost-effective solutions to take advantage of the material and energy without causing any impact on the environment.

4.1.2 Presentation of the cement plant in the study area

The closest cement plant to the Study Area is located in the province of Beni Mellal and is 81 km from the Study Area landfill (**Figure 5**). The potential for

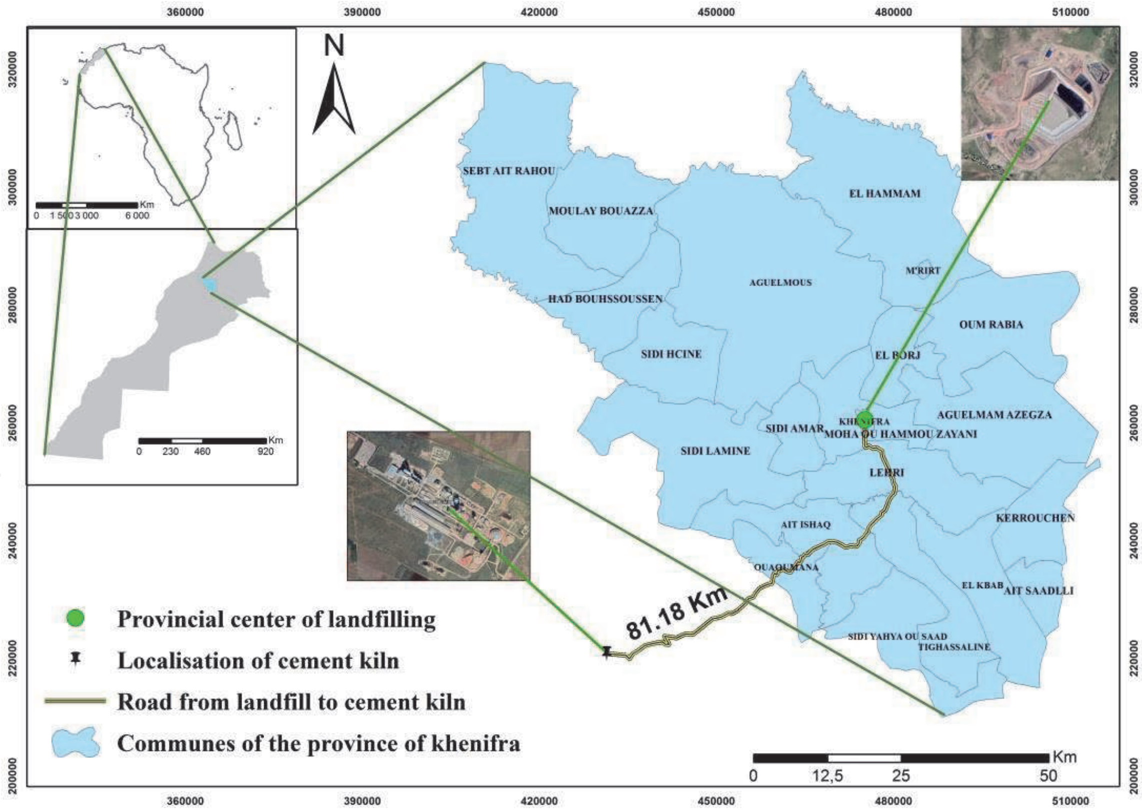

Figure 5.
Location of the study area and cement plant.

cement production at the plant is 1,600,000 million tonnes per year. The dry process is used to produce clinker. Calcination is done in a rotary kiln using fossil fuels (petroleum coke) (**Figure 6**).

4.1.3 Dry fractions potential in the study area

The scenario taken for this work is the recovery of all dry fractions that can be extracted from household waste following a sorting into two fractions (**Figure 7**). The percentage of dry fractions in household waste in Morocco is 30% of the total flow of household waste [30]. The lower caloric value (LCV) of these fractions has been determined in the laboratory according to the EN 15400 standard [34] the value found is 4454 kcal/kg.

The annual RDF potential in the study area is estimated based on the population of the municipalities in the province and the national average waste generation in urban and rural areas. The results of the RDF production estimated are presented in **Table 2**.

4.1.4 Calculation method

In order to demonstrate the economic and environmental benefits of co-incineration of RDF in cement kilns, several aspects will be evaluated in this case study. The economic gain of the cement plant and the carbon dioxide reduction will be determined. Several data have been collected in order to complete this study, including information on the cement plant in the study area (petroleum coke consumption, LCV of petroleum coke, clinker production, etc.), data on waste management in Khenifra province (potential in combustible fraction, PCI of RDF waste, etc.).

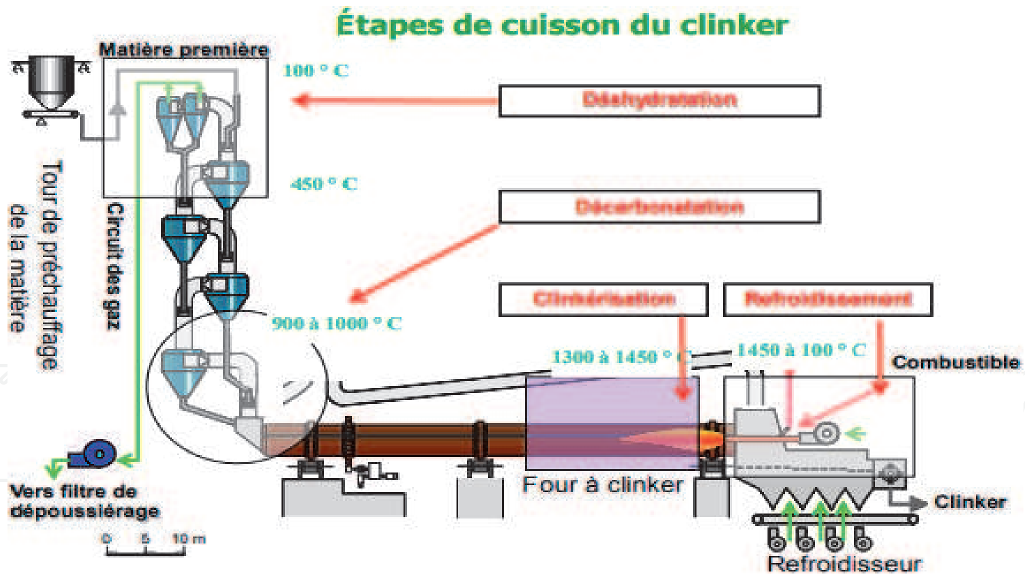

Figure 6.
Clinker firing stage in the cement plant.

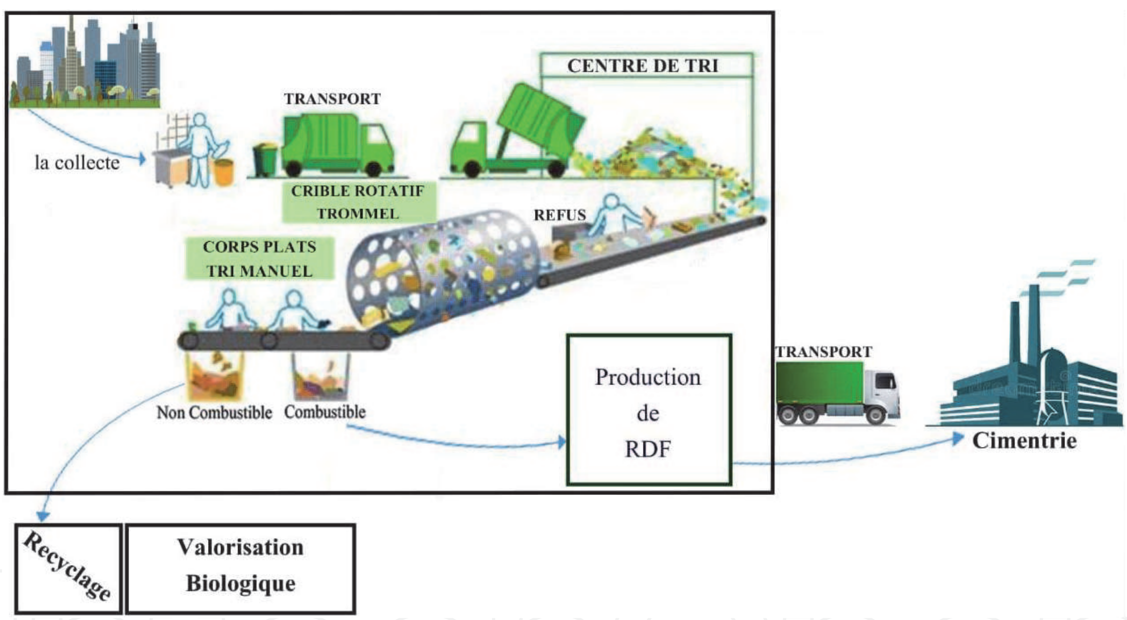

Figure 7.
RDF production scenario.

An economic model has been proposed taking into account the quantity of RDF produced, cost savings of fossil fuels, CO_2 emissions. Formula (1) is used to calculate the net savings of the cement plant.

$$\begin{aligned} \text{Net savings} = &\big((\text{Savings on traditional fuels} + CO_2 \text{ emission cost reduction} \\ &-\text{RDF production cost reduction}) * (100 - \text{Energy loss})\big)/100 \end{aligned} \tag{1}$$

4.1.4.1 The substitution rate

The substitution rate of RDF in cement plants can reach very high percentages up to 45% depending on the process. In the case of the present study, a substitution

Communitie	Number of communities	Population 2019 [33]	Rate of waste generation kg per capita per day [6]	Waste generation in tons/ year*	RDF production in Tons/ year**
Urban communities	2	174,176	0.76	48,316	1 4495
Rural communities	20	205,463	0.29	59,584	17,875
Total of RDF in the study area				32,370	

*Calculated using the number of population and the waste generation ratio.
**Calculated using waste generation and percentage of RDF in waste (30%).

Table 2.
Estimated RDF production in the Study Area.

rate of 15% was chosen based on the results of the study by Kara [8] and Hemidat et al. [9] who found that 15% is the most optimal substitution rate from a technical and environmental point of view [8, 9].

4.1.4.2 RDF requirement in cement plant

In order to calculate the amount of RDF required achieving 15% substitution percentage of pet coke, the energy content of RDF was taken into account based on the LCV value determined for the waste in the study area. In fact, a ton of pet coke does not have the same calorific value as a ton of RDF. The data used for the calculation of RDF required to substitute 15% of the pet coke are presented in **Table 3**.

4.1.4.3 Energy requirement

The amount of energy required to produce one kilogram of clinker is 730 kcal/kg. Therefore the amount of energy to be extracted from RDF with 15% substitution is given in Eqs. (2) and (3).

$$\mathrm{ERDF} = \frac{730 \times 15}{100} = 109.5\ \mathrm{kcal} \tag{2}$$

$$\mathrm{EPC} = \frac{730 \times 85}{100} = 620.5\ \mathrm{kcal} \tag{3}$$

where ERDF is the energy required from RDF with a 15% substitution rate to produce one kilogram of clinker; EPC is the energy required from pet coke with a substitution rate of 85% to produce one kilogram of clinker.

Energy required to produce one kilogram of clinker [35]	730 kcal/kg
LCV of petroleum coke	7500 kcal/kg
LCV of RDF	4454 kcal/kg
Annual production of petroleum coke	1,000,000 tons

Table 3.
RDF requirement calculation data.

4.1.4.4 Requirement in mass quantity

The NCV of the RDF in the study area is 4453 kcal/kg, hence, the amount of RDF required to produce one kilogram of clinker in the case of 15% substitution is given by Eq. (4).

$$\text{Mass of RDF corresponding to 109.5 kcal} = 109,5\ \text{kcal} \times \frac{1}{\text{LCV RDF}} = 0.024\text{kg} \tag{4}$$

where LCV RDF is the lower calorific value of RDF (for the case of this study, it equals 4454 kcal/kg).

The quantity of pet coke required is given according to Eq. (5).

$$\text{Mass of pet coke corresponding to } 620.5\ \text{kcal} = 620.5\ \text{kcal} \times \frac{1}{\text{LCV PC}} = 0.083\ \text{kg} \tag{5}$$

where LCV PC is the lower calorific value of Pet coke (for the case of this study it is equal to 7500 kcal/kg).

The production of one ton of clinker requires the mixture of 0.024 ton of RDF and 0.083 ton of pet coke.

4.1.4.5 Fuel consumption as a function of time

The production capacity of the cement plant close to the study area is 1,600,000 tons of cement per year, the calculation to be made in this study will concern the economic cost of using RDF to produce 1 million tons of clinker per year. **Table 4** shows the daily and hourly production of clinker. The cement plant is shut down for a period of one month in order to maintain the combustion furnace.

On the basis of clinker production as a function of time, the tonnage of fuel used will be deducted according to Eq. (6).

$$\text{fuel consumption per hour} = \text{Production of} \frac{\text{clinker}}{\text{hour}} \times \text{The amount of RDF needed to produce one tonne of clinker} \tag{6}$$

$$\text{RDF consumption per hour} = 124.37 \times 0.024 = 2.99\ \text{tons per hour} \tag{7}$$

The same formula (6) is used to calculate pet coke consumption per hour:

$$\text{pet coke consumption per hour} = 124.37 \times 0.083 = 10.32\ \text{tons per hour} \tag{8}$$

4.1.4.6 CO_2 emissions

The amount of carbon dioxide (CO_2) saved has been estimated by assuming that 70% of one kilogram of petroleum coke is emitted as CO_2 [8]. It is then converted

Production (tons/year)	Production (tons/day)	Production (tons/hour)
1,000,000	2985	124.34

Table 4.
Clinker production per year, per day and per hour.

into CO_2 savings in the form of an emission of 1 kg of CO_2, which is estimated at USD 0.015 [36].

5. Results and discussion

As shown in the experimental study by Hemidat et al. [9] and Kara [8], the use of 15% RDF as a substitute for pet coke for the generation of thermal energy for clinker production does not cause any quality problems [8, 9]. The consumption of pet coke in kg/hour is 10,320 if the substitution rate is 15% and 2990 kg/hour of RDF which will save 1782 kg/hour of petroleum coke (**Table 5**).

Hence, the use of 15% RDF will save 1782 kg/h of pet coke, so the annual saving of pet coke is:

$$1.782 \frac{\text{tons}}{\text{hour}} \times 24 \frac{\text{hour}}{\text{day}} \times 335 \frac{\text{days}}{\text{year}} = 14327.28 \frac{\text{tons}}{\text{year}} \quad (9)$$

As a result, 15,610. 32 tons of pet coke will be saved annually if 15% RDF is used in the cement plant kiln.

Table 6 shows the results of the calculation of the CO_2 emission parameters as well as the net savings in USD per hour.

The price of petroleum coke is variable and depends on the price of oil. In this study a price of 150 USD/ton was taken as the annual average selling price of petroleum coke, so the annual saving in terms of petroleum coke if 15% RDF is used as a substitute is:

$$14\,327.28 \frac{\text{tons}}{\text{ans}} \times \frac{150\text{USD}}{\text{ton}} = 2,149,092 \text{ USD/year} \quad (10)$$

Since the consumption of RDF is 2.99 ton/h, then the annual consumption is:

$$\text{annual consumption of RDF} = \frac{2.99\text{tons}}{\text{h}} \times \frac{24\text{h}}{\text{day}} \times \frac{335\text{day}}{\text{year}} = 24\,039.6 \text{ tons/year} \quad (11)$$

	Rate of RDF substitution %	Consumption of pet coke %	Consumption of pet coke (kg/h)	Consumption of RDF (kg/h)	Pet coke saving (kg/h)
Scenario 1	0	100	12,102	0	0
Scenario 2	15	85	10,320	2990	1782

Table 5.
Calculation results for the pet coke saving.

	Rate of RDF substitution %	Pet coke saving (kg/h)	Pet coke saving (USD/h)	CO_2 emissions saving (kg/h)	CO_2 emissions saving (USD/h)	Cost of RDF production (USD/h)	Loss of efficiency %	Net saving (USD/h)
Scenario 1	0	0	0	0	0	0	0	0
Scenario 2	15	1782	151.47	1247.7	18.72	247.68	3	37.19

Table 6.
The relation between emission and saving in the view of CO_2.

The market price of one ton of RDF is 24 USD/ton, hence, the annual purchase price of RDF is:

$$\frac{24\ 039.6\text{tons}}{\text{year}} \times 24\text{USD} = 576,950.4\ \text{USD/year} \tag{12}$$

The real financial economy is:

$$2,149,092\ \frac{\text{USD}}{\text{year}} - 576,950.4\frac{\text{USD}}{\text{Year}} = \frac{1,572,141.6\text{USD}}{\text{year}} \tag{13}$$

The results obtained show the real savings achieved through the use of RDF in the cement plant.

In addition, savings related to the substitution of petroleum coke by the more expensive RDF, indirect savings related to CO_2 emissions can be achieved.

Given that the price of a ton of pet coke is USD 150, with 15% substitution by RDF.

Therefore, the financial saving on pet coke is:

$$\frac{1\ 782\text{kg}}{\text{h}} \times \frac{0.15\text{USD}}{\text{Kg}} = 267.3\ \text{USD/h} \tag{14}$$

The amount of CO_2 emissions to be saved is:

$$\frac{1\ 782\text{kg}}{\text{h}} \times 0.7 = 1\ 247.7\ \text{kg/h} \tag{15}$$

The saved cost related to CO_2 emissions is:

$$\frac{1\ 247.7\ \text{kg}}{\text{h}} \times \frac{0.015\text{USD}}{\text{kg}} = 18.72\frac{\text{USD}}{\text{h}} \tag{16}$$

The cost of RDF is:

$$\frac{10\ 320\text{kg}}{\text{h}} \times \frac{0.024\text{USD}}{\text{kg}} = 247.68\ \text{USD/h} \tag{17}$$

The loss of efficiency is given as follows:

$$20\% \times \text{RDF\%conumtion} \times 100 \tag{18}$$
$$(0.2 \times 0.15) \times 100 = 3\%$$

The net saving per hour is:

$$\begin{aligned}\text{Net Savings} = ((&\text{Savings on Conventional Fuels} + CO_2\ \text{Emission Cost Reduction} \\ &- \text{RDF Production Cost Reduction}) * (100 - \text{Loss of Energy}))/100\end{aligned} \tag{19}$$
$$\frac{[(267.3 + 18.72 - 247.68\ ) \times (100 - 3)]}{100} = 37.19\ \text{USD/h}$$

The energy recovery of RDF in the cement plant has shown the economic and environmental advantage of substituting fossil fuels (Petroleum Coke) by alternative fuels (RDF). This case study shows that the cement plant can save its pet coke consumption as well as CO_2 emissions with a saving of 37 USD/hour. Such a study on a cement plant in Turkey showed that it can save 19 USD/h [8]. In Jordan, Hemdiat et al. found that the savings that a cement plant can make by substituting 15% RDF for petroleum coke can be as high as 389 USD/h [9]. The results found and the potential for the combustible fraction in Moroccan waste [6, 30] are encouraging in order to develop an RDF production chain in all the regions where there are cement plants in Morocco. In addition to the advantage of sustainable disposal of household waste, other types of waste such as medical waste, pandemic waste such as COVID-19, and sludge from wastewater treatment plants can be thermally treated in the kilns of cement plants [37, 38].

6. Conclusion

Energy recovery is considered to be a sustainable way of managing household waste. The study concerns the case of a developing country with several problems related to the waste management sector. In this chapter, the RDF recovery process in cement kilns has been studied for the case of a region in Morocco. The results of the evaluation have led to the conclusion that the substitution of petroleum coke with RDF with a percentage of 15% saves 389 USD/hour. In addition to these benefits, the co-incineration of RDF reduces the volume of waste, increases the life of the landfill and provides sustainable and renewable energy.

Acknowledgements

The authors are grateful to the cement plant CIMAT, the province of Khenifra and Team of Agro industrial and Environmental Processes of Sultan Moulay Slimane University.

Conflict of interest

The authors declare no conflict of interest.

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