Waste Biorefinery in Makkah: A Solution to Convert Waste produced during Hajj and Umrah Seasons into Wealth

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Abstract

The concept of waste biorefinery is known as one of the several energy recovery technologies capable of producing multi products in the form of biofuels and value-added products treating different fractions of municipal solid waste (MSW). The conversion technologies such as anaerobic digestion (AD), pyrolysis, transesterification, incineration treat food, plastic, meat, and lignocellulosic wastes to produce liquid, gaseous and solid biofuels. Makkah city landfills receive about 2750 tons of waste every day. Whilst during the Ramadan and Hajj seasons, these quantities become 3000 tons and 4706 tons per day respectively. More than 2.5 million animals were sold for slaughtering in 2014 Hajj, and their blood and organic solid waste were disposed untreated. Similarly, around 2.1 million plastic Zam-Zam cups were wasted every day during the 2014 Ramadan time. In the first three days of 2014's Ramadan, 5000 tons of food was wasted only in Makkah municipality. Collectively, about 3853 tons of waste were generated each day during 2014 Hajj and Ramadan. The waste from Al-Haram and Al-Masha'ir (Mina, Muzdalifah and Arafat) and their surroundings was mainly composed of organics (upto 68.5%). There is no waste-to-energy facility existing in Saudi Arabia. The waste biorefinery in Makkah will divert upto 94% of MSW from landfill to biorefinery. The energy potential of 2171.47 TJ and 8852.66 TJ can be produced if all of the food and plastic waste of the Makkah city are processed through AD and pyrolysis respectively. The development of AD and pyrolysis under waste biorefinery will also benefit the economy with gross savings of 405 and 565.7 million SR respectively, totalling to annual benefit of 970.7 million SR. Therefore, the benefits of waste biorefinery in Makkah city and other parts of the Saudi Arabia are numerous including the

development of renewable-energy science and research, solving solid waste problems, new businesses and job creation opportunities and minimizing environmental pollution.

Introduction

In Saudi Arabia, millions of muslims gather every year to perform worship from all over the world at Al-Haram (Holy Mosques in Makkah and Medina) and Al-Masha'ir (Mina, Arafat and Muzdalifah) (Figure 1). The area of Al-Haram mosque in Makkah, including indoor and outdoor prayer space is 356,800 square meters, where more than 2 million muslims can worship, especially during the Ramadan (the 9 month of the Islamic lunar calendar) and Hajj (the 12 month of the Islamic lunar calendar). Hajj is one of the largest gatherings in the world every year. More than 23,000 municipality workers and 450 scouts participated only in cleaning operations for the gathering of 2.1 million muslims in 2014 Hajj (Hazaimeh, 2014). The Makkah city landfills receive about 2750 tons of waste every day. While, these quantities become 3000 tons and 4706 tons per day during the Ramadan and Hajj respectively. The peak of waste generation occurs during 8 - 13 Zulhijjah (the time of Pilgrimage) and last ten days of Ramadan (the month of fasting).

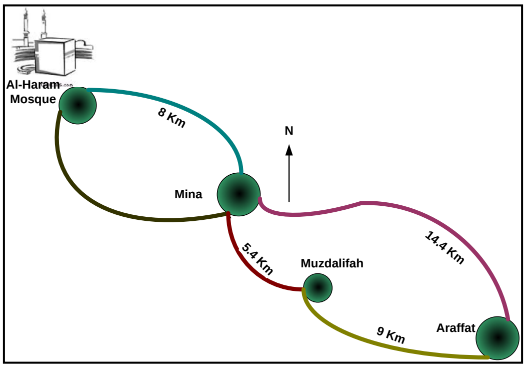

Figure 1. Map of Hajj route and destinations

In 2014 Hajj, more than 2.5 million animals were sold for slaughtering (Amtul, 2014). Similarly, around 2.1 million plastic Zam-Zam cups were wasted every day during the 2014 Ramadan. Around 5000 tons of food was wasted only in the Makkah municipality in the first three days of 2014's Ramadan, (Irfan, 2014). As a whole, during the 2014 Ramadan and Hajj time about 3853 tons of waste were generated every day. The sources of these wastes are food (44%), plastics (23%), paper and cardboards (16%), leather and rubber (8.5%), textiles (2%), glass (1.2%), aluminium (1.4%) and others (3.5%) (Mashat, 2014; Abdul Aziz et al., 2007). While, during the normal days, the range of waste generation from Al-Haram mosque was food (10-21%), plastics

(38-46%) and paper (11-25%) (Abu-Rizaiza and Al-Ghamdi, 2001). During the 2014 Hajj, the estimated waste generation rate per pilgrim was 2.24 kg per day with total waste generation of 141.2 thousand tons.

The waste collection becomes a challenging task for authorities during Hajj and Ramadan seasons. The normal waste management principles don't apply in such conditions, where millions of Muslims are gathered in certain locations. Therefore, there is an immediate need of waste biorefinery in Makkah city for the sustainable disposal of these wastes with value-added material and energy recovery. The benefits of waste biorefinery in Saudi Arabia are numerous such as the development of renewable-energy science and research, solving solid waste problems, new businesses and job creation opportunities, and minimizing environmental pollution.

Methodology

The year 2014 is considered as a baseline year for the forecasting of the number of Pilgrims and waste generation until 2024. The number of pilgrims have increased with a yearly rate of 1.15% from 1993-2014 (CDSI, 2011). The total waste generation during the Hajj times (one month in Lunar Calendar) in Al-Haram and Al-Mashair has increased from 91.34 to 114.24 thousand tons with an annual rate of 2.38% from 1993-2006 (Abdul Aziz et al., 2007). This average percentage (2.38%) of 14 years' time is used to forecast the total waste generation in Hajj periods of 2007-2014 (Table 1). The rate of pilgrim's increase (1.15%) along with rate of total waste generation in Hajj (2.38%) is used to calculate the waste generation per pilgrim from 2007-2014 and then forecasting it further until 2024. The waste composition values (Figure 2) are used to calculate the total waste amount of each waste category/type.

Table 1. The total pilgrims and waste generation in the month of Dhu al-Hijjah

Hijri year	Gregorian years	Total Pilgrims (million)	Total waste in Dhu al-Hijjah (thousand tons)
1415	1995	1.86	110.53
1420	2000	1.91	138.5
1425	2005	2.25	104.79
1430	2009	2.31	125.51
1435	2014	2.10	141.18
1440	2019	2.23	158.81
1445	2024	3.25	178.63

The values of physical and chemical compositions of food waste generated in Makkah city were assumed to be similar to the work of Khan and Kaneesamkandi (2013), which also analysed the biodegradable waste of Saudi Arabia (Table 2). These values were used to select the conversion technologies suitable to different fractions of municipal solid waste (MSW) under waste biorefinery.

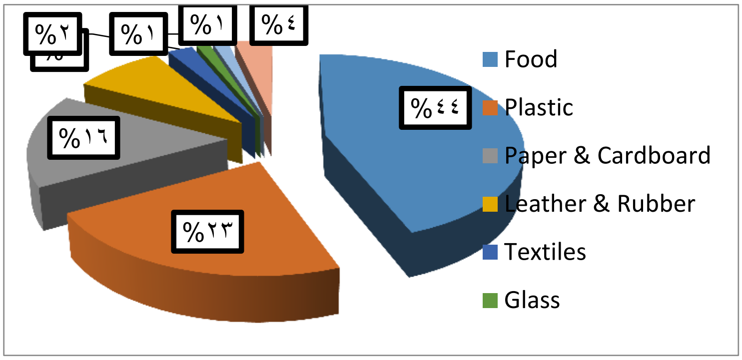

Figure 2. Average waste composition from all areas of Makkah during Ramadan and Hajj

There are many established waste-to-energy technologies all over the world such as anaerobic digestion (AD), incineration, gasification, pyrolysis, fermentation, transesterification, etc. Waste conversion to bioenergy takes place using three main conversion processes: thermochemical, biochemical, and physicochemical processes (Nizami et al., 2014). Thermochemical processes use high temperatures to convert waste feedstock to bioenergy, typically in the form of electricity and heat and bioproducts. Within thermochemical conversion, three processes are available: pyrolysis, gasification and combustion. Biochemical technologies use biological agents to convert biomass feedstock to energy, typically in the form of liquid and gaseous fuels.

Table 2. Physical and chemical composition of food waste

Physical composition (٪)		Chemical composition (٪)	
Rice	38.72	Moisture	38.4
Bakery products	18.74	Carbohydrates	25.56
Meat	25.15	Crude Protein	17.26
Fat	13.03	Crude fat	15.27
Bones	2.19	Fiber	0.3
Fruit and vegetables	2.16	Ash	3.21

Biochemical conversion includes anaerobic digestion and fermentation processes. Physicochemical technologies use chemical agents to convert biomass feedstock to bioenergy, typically in the form of liquid fuels. Transesterification is widely used in the physicochemical conversion pathway (Nizami et al., 2014). Three technologies; anaerobic digestion, pyrolysis and transesterification are selected based on waste type, composition and generation rate (Table 2 & Figure 2).

Results and Discussion

Pilgrims and Waste Generation

The total population of Saudi Arabia has reached to 31 million in 2014, with 1.96 million population of Makkah city. In 2014, the total estimated waste generation in Makkah city was 1.23 million tons, including waste generated by local population (1 million tons), pilgrims (0.14 million tons) and Ramadan visitors (0.09 million tons). This waste rate is projected to become more than double with 2.6 million tons in 2020 based on projected local population, pilgrims and umrah visitors (Table 1). The food (44%) and plastic (23%) wastes are one of the prominent waste streams (Figure 2), with amounts of 546.53 and 279.44 thousand tons respectively among the overall collected waste in Makkah city throughout the year. The Hajj and Ramadan periods add a significant amount of food and plastic wastes due to food serving in disposable plates and cups.

In Al-Masha'ir, most of the generated waste is from Mina (Table 3), where pilgrims stayed most of their time. On average, 3409.9 and 1772.4 tons of food and plastic was wasted each day during 2014 Ramadan and Hajj. The alarming news is the wastage of 35-40% cooked rice annually with the total amount of 3 million tons per year, the worthy of 1.6 billion SR (Saudi Gazette, 2014). Such a waste with high fraction of organic contents (upto 68.5%), especially the food waste with high moisture content (38.4%), carbohydrates (25.6%) and proteins (17.3%) make it very suitable feedstock for waste-to-energy technologies (Table 2).

Nevertheless, the animal slaughtering also produces animal related waste, i.e. bovine, blood wastes, etc. in huge quantities each year, especially during the Hajj periods. According to Amtul (2014), more than 2.5 million, animals were sold for slaughtering in 2014 Hajj. Typically, 12% waste per body weight is generated in sheep and goat slaughtering, while cattle slaughtering generate 38 percent waste (Singh, 2013). This waste includes rumen, blood, stomach, intestine, tallow and fats. There is no such information available on the amount of waste generated by slaughtering during the Hajj periods. However, it is evident that this animal blood and solid waste quantities are huge in Saudi Arabia, and they are currently disposed without treatment.

Table 3. Total waste generation from Arafat, Muzdalifah and Mina during Hajj seasons

Hajj		Waste Generation (thousand tons)		
Hijri year	Gregorian year	Arafat	Muzdalifah	Mina
1415	1995	5	0.3	21
1416	1996	5.5	0.4	22
1417	1997	6	0.45	31
1418	1998	5	0.4	22
1419	1999	6	0.35	22.5
1420	2000	8	5	18.5
1421	2001	7	5.5	20
1422	2002	7	6.5	21
1423	2003	11	8	21.5

Proposed Waste to Energy Technologies

Anaerobic Digestion (AD) of Food Waste

The anaerobic digestion (AD) process converts organic matter into biogas that can be used for heating, generating electricity and as a biofuel (Nizami et al., 2009). There are different types of anaerobic digesters that can carry out this digestion process; such digesters are classified based on whether it is a wet or dry process, a batch or continuous process, the number of phases or stages in the digestion, their operating temperature, retention time and organic loading rate (Nizami et al., 2010 & 2011; Nizami and Murphy, 2010). In Saudi Arabia, AD technology is suitable for food waste due to its high organic contents and the physical and chemical characteristics (Table 2). Moreover, a protein-rich waste in form of blood waste (from animal slaughtering) can also be digested anaerobically as single substrate or combined with food waste. A production of 98.7 million m^3 of biogas with total energy of 2171.5 TJ or 0.6 TWh can be achieved, if all of the food waste (0.55 million tons/year) is utilized in AD (Box 1). Nonetheless, a gross saving of 405 million SR per year can be added to the country's economy by developing biogas plant in the Makkah city (Box 2).

Box 1. Biogas and pyrolysis fuel oil production and their total energy potential (2014)

Biogas yield
Total food waste generated = 0.5465 million tons/year
Typical biogas value from food waste = 180.6 m^3/ton (Banks, 2009)
Total biogas production from food waste = 98.70 million m^3/year
Biogas energy potential = 22 MJ/m^3 of biogas or 6.1 KWh/ m^3 of biogas (Banks, 2009)
Therefore, total annual biogas energy potential = 2171.47 TJ or 0.60 TWh
Pyrolysis fuel oil yeild
Total plastic generated = 0.2794 million tons/year
Typical fuel oil production from pyrolysis (1kg of mixed plastic (PE, PP and PS type) = 0.8 Kg oil (Nizami et al., 2014b)
Total pyrolysis oil potential = 223.55 million Kg/year
Pyrolysis oil energy potential= 39.6 MJ/ Kg ((US-EPA, 2012)
Therefore, total annual pyrolysis energy potential= 8852.66 TJ or 2.46 TWh

Pyrolysis of Waste Plastics into Fuel-Oil

The waste plastic is the second large municipal waste streams in the Saudi Arabia and even in Makkah city at the rate of 279.4 thousand tons per year. Final disposal of such wastes represents operational and environmental overburden to most landfills. The production and consumption of plastics during the Hajj and Ramadan in form of Zam-Zam drinking cups and disposable plates have increased to an alarming level over the last decade. In pyrolysis process, waste plastic is decomposed thermochemically in the absence of air at temperatures of upto 500 ^{0}C and converted into liquid (fuel-oil), solid (charcoal) and gaseous (syngas) fractions. The fuel-oil is similar to diesel, with lower sulphur and higher cetane value in comparison to traditional diesel. A production of 223.5 million kg of fuel-oil with total energy of 8852.7 TJ or 2.5 TWh can be achieved if all of the waste plastic generated in Makkah city (0.2794 million tons/ year) is utilized in the pyrolysis process (Box 1). A gross saving of 565.7 million SR per year can be added to the country's economy by developing pyrolysis plant in Makkah city (Box 3).

Box 2. Cost benefit analysis of producing biogas from food waste in KSA

Solid waste management (SWM) cost	
*SWM budget =	702.31 million SR / year
Cost of waste dumping/disposal =	572.36 SR / ton
Total amount of food waste =	0.5465 million tons
Total cost of food waste =	312.81 million SR
Therefore, annual direct saving by discontinuing the food waste dumping =	312.81 million SR
Biogas technology revenue	
Typical energy value of food waste anaerobic digestion =	958.6 KWh/ton
Total energy value of food waste =	523.90 million KWh
Electricity cost	
Current domestic electricity cost =	0.22 SR/KWh
Total benefit =	115.26 million SR
**Waste collection, plant operational and maintenance cost =	23.05 million SR
Therefore, the total revenue from biogas technology =	92.21 million SR
Gross benefit	
Gross benefit =	Annual direct savings + annual revenue fro biogas technology
	405.018 million SR / year

* The budget of SWM assumes 30٪ of the total annual budget considering, which is 29 billion SR for Sewage and SWM activities (Maria, 2013). We worked out SWM on the basis of the waste fraction of Makkah total waste / whole Saudi Arabia waste in 2014.

** Estimated to be 20٪ of the energy benefit value

Biodiesel from Used Cooking Oil and Fats

A large fraction of the country MSW is also consisted of used cooking oil, from households and restaurants, and fats from food and animal waste. Transesterification is a process of converting such fats and oils into biodiesel by recycling polyesters into individual monomers. It is a chemical reaction by which fats or oils are reacted with short-chain alcohols such as methanol or ethanol. Glycerol, soap, excess alcohol is also produced besides biodiesel, which are removed by using different standard methods. There are no data and information available regarding the amounts and compositions of used cooking oil, fats and meat waste separately.

Waste Biorefinery

There are certain limitations associated with each waste to energy technology based on process efficiency, commercializing, feedstock, infrastructure requirements and end use applications. It is difficult for an individual technology to achieve zero waste concept and competes with other renewable-energy sources like wind, solar, etc. The technological solution to these limitations is to select the conversion technologies based on waste composition and characterization and integrate technologies in a waste biorefinery. A biorefinery is basically a cluster of conversion technologies producing chemicals, fuels, power, products, and materials from different feedstock at one platform. A waste biorefinery is proposed for Makkah city (Figure 3), which utilize the city MSW during the normal days, Hajj and Ramadan periods. Five different conversion technologies such as AD, composting, pyrolysis, rendering and transesterification and algae biofuel are placed in the waste biorefinery to treat food, plastic, used-oil and animal waste respectively (Figure 3).

Box 3. Cost-benefit analysis of producing fuel-oil from pyrolysis of waste plastics

Solid waste management (SWM) cost	
*SWM budget =	702.31 million SR / year
Cost of waste dumping/disposal =	572.36 SR / ton
Total amount of plastic waste =	0.2794 million tons
Total cost of plastic waste =	159.94 million SR
Therefore, annual direct saving by discontinuing the food waste dumping =	159.94 million SR
Pyrolysis technology revenue	
Typical energy value of fuel oil from plastic waste =	11000 KWh/ton
Total energy value of plastic waste =	3073.84 million KWh
Electricity cost	
Current domestic electricity cost =	0.22 SR/KWh
Total benefit =	676.24 million SR
**Waste collection, plant operational and maintenance cost =	270.50 million SR
Therefore, the total revenue from pyrolysis technology =	405.75 million SR
Gross benefit	
Gross benefit =	Annual direct savings + annual revenue from pyrolysis technology
	565.69 million SR / year

*Worked out on the basis of the waste fraction of Makkah waste/whole Saudi Arabia in 2014.

**Estimated to be 40% of the energy benefit value

The waste will be tipped and segregated automatically based on the material properties and send to the designated technologies. The energy generated in combined heat and power (CHP) plant in form of electricity and heat will be utilized in pyrolysis, rendering and transesterification, algae production, and AD. The CHP will be running on the fuel (fuel-oil) generated from plastic pyrolysis. The organic fractions such as food, paper, animal blood and agriculture waste will be pretreated and separated into liquid and solid streams. The liquid stream will be injected into the AD reactor to produce biogas at a thermophilic temperature. The biogas will be upgraded to be used as compressed natural gas (CNG) in vehicles. During biogas upgrading and CHP plant operation, the CO_2 will be captured using water scrubbing method and utilized in the algae production. The liquid left over from the AD reactor will provide a medium for algae growth. The solid stream after the organics pretreatment will be used in enclosed-vessel thermophilic composting, and the product (compost) will be used as organic fertilizer for horticulture and agricultural purposes. The animal waste such as bovine, used-oil from homes and restaurants, and algae-oil will be converted into lard, tallow and biodiesel using rendering and transesterification process (Figure 3). The biodiesel will be cleaned and used as vehicular fuel. The surplus electricity generated in the CHP plant will be connected to the national grid. This proposed waste biorefinery in Makkah will not only be sufficient to run its own various processes without external energy, but also provide surplus liquid (biodiesel) and gaseous (CNG) fuels and value-added products (organic fertilizer, lard, tallow, syngas and charcoal). The CO_2 capturing and use of liquid waste for algae growth will reduce the greenhouse gas (GHG) impact and pollution of the waste biorefinery.

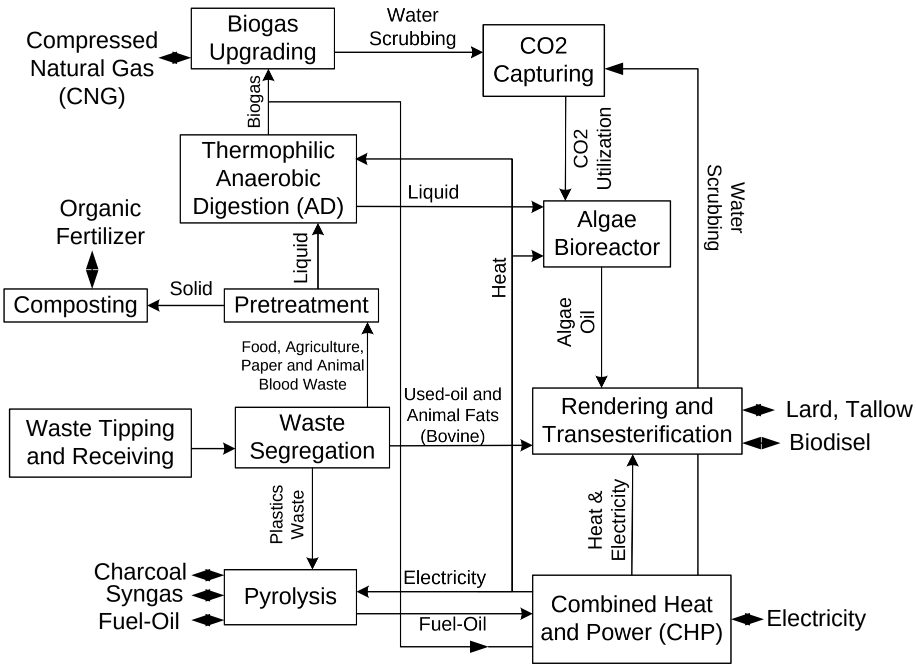

Figure 3. The integrated waste biorefinery in Makkah City

Conclusion

A review of the perspective of waste to energy technologies in Makkah city of Saudi Arabia is carried out based on the limited available data. However, the real selection of the conversion technologies will be carried out in conjunction with the fieldwork on waste characterization and laboratory analysis of selected technologies. The food (44.2٪) and plastic (22.6٪) wastes are the two main waste streams in Makkah with total estimated annual production of 564 and 279 thousand tons respectively by local population, pilgrims and umrah visitors. The overall waste produced is highly organics (68.5٪) including food, paper, cardboard and leather and food waste covers most of it with a high portion of carbohydrates, proteins and fats. An estimated production of 98.7 million m^3 of biogas with total energy of 2171.5 TJ can be achieved annually, if all of the food waste produced in Makkah city is utilized in anaerobic digestion. Similarly, 223.5 million kg of fuel-oil, i.e. equivalent to diesel with total energy of 8852.7 TJ can be produced annually if all of the waste plastic of Makkah city is processed in the pyrolysis technology. The development of biogas and pyrolysis technologies will also benefit the economy with gross savings of 405 and 565.7 million SR respectively, totalling to annual benefit of 970.7 million SR. The concept of waste biorefinery can be applied in other cities as well, which will not only solve the MSW problems, but also contribute significantly to the national energy requirement and economy of the Kingdom.

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