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Faculty of Tropical AgriSciences

Czech University of Life Sciences Prague
Faculty of Tropical
AgriSciences

Refuse Derived Fuel as an alternative solution to dispose of agricultural plastic waste in developing countries

BACHELOR'S THESIS

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Author:
Marina Pleshkova

Supervisor:
doc. Bc. Ing. Tatiana Ivanova, Ph.D.

Declaration

I hereby declare that I have done this Thesis entitled “Refuse Derived Fuel as an alternative solution to dispose of agricultural plastic waste in developing countries” independently, all texts in this Thesis are original, and all the sources have been quoted and acknowledged by means of complete references and according to Citation rules of the FTA.

In Prague 14th of August 2020

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Marina Pleshkova

Acknowledgement

I wish to express my sincere appreciation to my supervisor, doc. Bc. Ing. Tatiana Ivanova, Ph.D., for her patient guidance, invaluable advices, kindness and consistent support throughout the whole process of writing the Bachelor's Thesis. I would also like to thank my boyfriend Slava and my friend Nata, who were of great support in deliberating over our problems and findings, as well as providing happy distraction to rest my mind outside of my research.

Abstract

Agriculture is responsible for the intensive use of plastic materials to increase productivity. At the end of the service life, agricultural plastic waste (APW) accumulates and is mostly taken to landfills or disposed of on site, which has negative environmental consequences. Proper management of APW can reduce environmental damage as well as prevent economic losses.

This Bachelor Thesis entitled «Refuse Derived Fuel as an alternative solution to dispose of agricultural plastic waste in developing countries» was written in the form of literature review based on search and analysis of information from scientific articles obtained from the well-known professional journals. The present Thesis summarizes information about the potential use of waste as an alternative fuel in developing countries.

The work described the characteristics, composition, the production process of refuse derived fuel (RDF) and the main potential users of alternative fuel. Various parameters of RDF with coal and municipal solid waste (MSW) were compared such as: heating value (HV), moisture, and ash content. The environmental and economic indicators of the use of the new product were also analyzed.

The purpose of this work was to present a useful tool for effective and efficient APW management, which aims to reduce greenhouse gas emissions, reduce dependence on fossil fuels, and encourage the use of renewable energy sources.

Keywords: agricultural plastic waste, plasticulture, environmental pollution, waste management, waste to energy, refuse derived fuel

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List of the abbreviations used in the thesis

APW – Agricultural Plastic Waste

ASTM - American Society for Testing and Materials

CIS - Commonwealth of Independent States

CO_2 – Carbon Dioxide

EU – European Union

HHV - Higher Heating Value

HV - Heating Value

IEA - International Energy Agency

ISWA - International Solid Waste Association

GHG – Greenhouse Gas

LHV - Lower Heating Value

MSW – Municipal Solid Waste

NAFTA - North American Free Trade Agreement

PW – Plastic Waste

RDF – Refuse Derived Fuel

SWMR – Solid Waste Management Rules

t - tonne

1. Introduction

As a result of the expansion of industrial and agricultural activities, population growth and economic development (Zhao et al. 2016), the amount of plastic waste (PW) is increasing at an enormous rate and is becoming a major source of pollution of the entire planet (Wang et al. 2016).

Today, PW management is a global problem (Muise 2016, Blanco et al. 2018). Landfilling and on-site incineration are the most common methods, making the glorified durability of plastic a long-term cause of pollution and human health hazard (Dianda et al. 2018).

Many developed countries are trying to pay more attention to the creation of efficient and rational ways of recycling or treatment of waste (Sieradzka et al. 2020). One of these is RDF production (Zhao et al. 2016).

The driving force behind the production of RDF is the fact that this fuel can come from municipal solid waste, agricultural and industrial waste that includes plastics, paper, textiles, and other organic waste (Gendebien et al. 2003, Porshnov et al. 2018).

Moreover, RDF is a potential energy recovery resource, which implies a reduction in fossil fuel consumption and conservation (Thirugnanam & Pragasam 2013, Hemidat et al. 2019). The alternative fuel has a higher heating value (HHV) and a quite homogeneous physical and chemical composition, which leads to lower emissions of pollutants into the atmosphere (Caputo & Pelagagge 2002, Nithikul 2007).

The use of RDF as an energy source (Nithikul 2007) may have growth potential in developing countries, especially given the ability to diversify RDF processing options. But for efficient fuel operation it is necessary to use the correct composition (Brás I et al. 2017) and to follow the sequence of the processing, which particularly affects the quality of the finished product (Anasstasia et al 2020).

It is important to note that there is no advanced information about the individual disposal and conversion of APW into an alternative fuel at the moment. Due to the similarity of characteristics and compositions of APW and MSW, it is possible to collect them together and, as a consequence, recycle them together. This is why MSW processes are used to describe RDF’s characteristics, composition and production process in detail.

Based on current literature, as well as the results of various scientific papers and research, I analyzed and identified the main advantages of RDF in the fight against APW disposal and described them in the present Thesis.

2. Objectives of the Thesis

2.1. Main objective

The main objective of the Thesis was to undertake a survey on the current practices of production and use of refuse-derived fuel with a focus on sustainability of RDF potential for the purpose of APW utilization in developing countries.

2.2. Specific objectives

The main objective of the Thesis was accomplished through more specific objectives:

1. To analyze the characteristics and main compositions of RDF.
2. To analyze the main RDF production technologies considering different composition of waste.
3. To analyze the environmental impacts of the production and use of RDF.

3. Methodology

This Thesis was written as a literature review consisting of three main chapters that were further divided into sub-chapters. The Thesis was elaborated in accordance with the manual of the Faculty of Tropical AgriSciences for writing Bachelor's Thesis and all references included in this Thesis were cited according to the Citation Rules of the FTA for Theses in English (2017 manual). The methodology of the Thesis was based on the study of secondary data sources (mainly articles) obtained from the scientific databases such as ScienceDirect, Elsevier, Web of Science and Google Scholar. The search for scientific information was done by the key words: agricultural plastic waste, plasticulture, environmental pollution, waste management, waste to energy, refuse derived fuel and others. Some important information was summarized and presented in the form of Tables. The information obtained was processed and analysed. Important data was summarized and presented in the form of Tables.

4. Literature Review

4.1. Plastic in agriculture

4.1.1. Nature and Magnitude of the problem of plastic

Today, the polymer industry is one of the fastest growing, and the number of consumer industries covers almost all manufacturing, including agriculture (Bläsing & Amelung 2017).

The excitement caused by the distinctive characteristics of the plastic material: lightness, flexibility, strength, corrosion resistance, processing, low cost, as well as excellent electrical and insulation properties, waterproof. Thus, the plastics industry seeks to meet the current needs of humanity, jeopardizing the needs of tomorrow (Singh et al. 2018).

Based on data from Statista (2019), it may be noted that the global plastics production increased more than 200 times between 1950 and 2018, which accounted for 359 million metric tonnes (Figure 1) (Nagy & Kuti 2016).

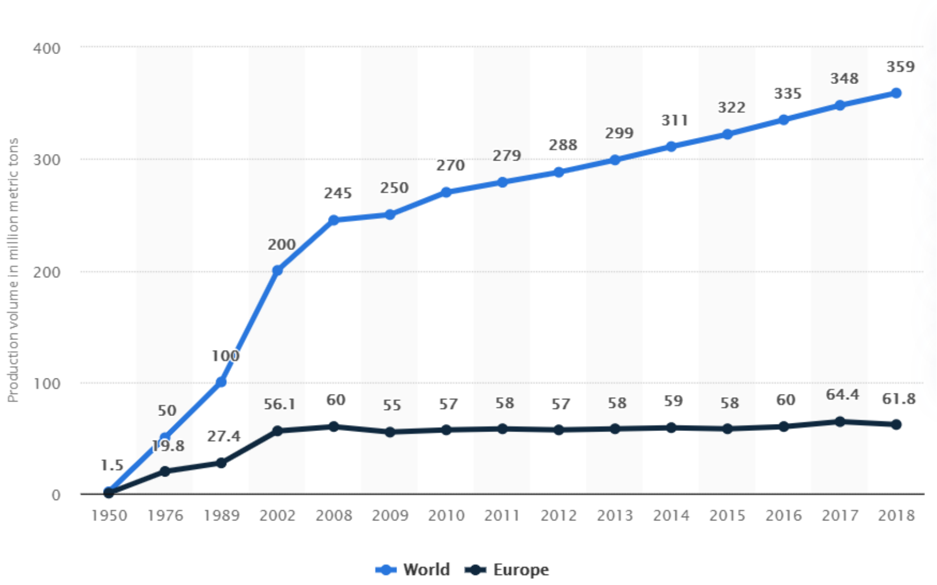

Figure 1. Global plastic production

Source: Statista (2019)

According to facts published by Plastics Europe (2019) in the distribution of the amount of global plastics production in 2018, it was found that half is produced in Asia, mainly in China and represents 30%. In turn, Indonesia produces about 9 million tonnes of plastic (2.5%). (Jain 2017, Lestari & Trihadiningrum 2019). NAFTA and European countries are also major producers (Figure 2).

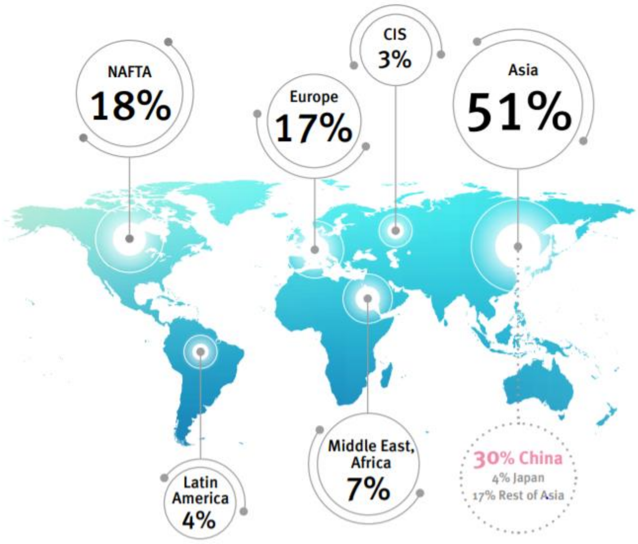

Figure 2. Distribution of global plastics production

Source: Plastics Europe (2019)

Meanwhile, agriculture uses 6.5 million metric tonnes of plastic annually, which is about 2% of the world's production (Bergmann et al. 2015; Plastics Europe 2019).

APW was first introduced in 1948 in the United States to cover small greenhouses with cellophane (Muise 2016). Following plastic products began to gain popularity in Japan, and then in other Asian countries, gradually replacing traditional materials such as glass, paper and straw (Park et al. 2008).

Demand continues to grow every year due to the increasing spread of intensive and semi-intensive farming practices (Vox et al. 2016; Blanco et al. 2018). The rapid emergence of plastic products on farms around the world is imperceptibly turns into a serious pollution problem. The absence or availability of an underdeveloped system for managing PW in agriculture leads to inefficient use of plastic, as well as improper collection, cleaning, sorting, and processing of APW. This leads to global environmental and economic problems (Muise 2016).

Pollution of the marine environment

Pollution of plastic materials was recognized as the first in the marine environment (Bergmann et al. 2015; Bläsing & Amelung 2017). Back in 1870, Jules Verne presented in his famous novel "Twenty Thousand Leagues Under the Seas" a graphic description of how floating debris is pulled from various sources and accumulated in oceans (Bergmann et al. 2015), as well as along the coastlines (McNeely et al. 2018).

According to Bläsing and Amelung (2017) about 10% of the global plastics production enters the oceans. In 2010, it was estimated that about 6-7 million tonnes of plastic got into the marine environment (Bergmann et al. 2015; Bläsing & Amelung 2017).

For example, based on data from Tibbetts (2015), Indonesia is second only to China in terms of marine plastic pollution. Brantas, Solo, Serayu and Progo are the country's four major rivers, which are included in the 20 most polluted rivers in the world.

A wide variety of sea taxa, including zooplankton, fish, birds, cetaceans, pinnipeds, and turtles, absorbs a range of oceanic plastics, and also become trapped, entanglement and cannot get out on their own (Bergmann et al. 2015; Jepsen & Nico de Bruyn 2019). Ingestion of PW disrupts the energy balance of animals, affects their behavior, or blocks the intestinal tract, leading to serious sublethal effects or even death and population decline (Jepsen & Nico de Bruyn 2019). A large concentration of ocean plastic on the seabed can stop gas exchange and change the functioning of the entire ecosystem (Jepsen & Nico de Bruyn 2019).

Soil pollution

The main reasons for the presence of plastic in agricultural soils are the use of soil additives such as wastewater irrigation, and the use of plastic mulches. All of this may contain a significant number of synthetic polymers (Fuller & Gautam 2016; Bläsing & Amelung 2017).

Plastic emits toxic and endocrine substances that negatively affect reproduction, growth of soil organisms and inhibit the microbiological activity of the soil (Bläsing & Amelung 2017). Furthermore, plastic is a sorbent for other toxic pollutants such as heavy metals and polychlorinated biphenyls and acts as a carrier of pollutants. When absorbed by biota, the adsorbed substances enter the food chain and endanger human and animal health (Bergmann et al. 2015; Nizzetto et al. 2016; Chae & An 2018).

4.1.2. Plasticulture and applications of plastic in agriculture

There is such a concept as Plasticulture meaning the use of plastic in agriculture, horticulture, water management, which contributes to improving the quality and quantity of products by reducing the consumption of herbicides and pesticides, protecting against various environmental conditions and so on (Bray 2017; Singh et al. 2018).

Based on data from several scientific papers, I compiled a table (Table 1) that shows major plasticulture technologies applications areas:

Table 1. Major plasticulture technologies applications areas

Applications areas	**Examples**
Water management	Lining of canals, ponds and reservoirs with plastics film[1]
	Irrigation tapes[1,2,3]
	Drainage pipes[1,3]
Nursery Management	Nursery bags, trays, plastic plugs, hanging baskets[3]
	Surface cover cultivation[1]
	Soil Solarisation[1]
	Plastics Mulching[2,3]
Controlled environment agriculture	Greenhouse films[1,2,3]
	Low tunnel films[2]
	Plant Protection nets (anti-hail, anti-bird, wind breaking, shading)[3]
	Direct covering[3]
Post-harvest Management	Plastics crates, bins, boxes, leno bags[1,2,3]
	Atmospheric Packaging[1]

Source: Author, based on [1]Scarascia-Mugnozza (2011); [2]Bray (2017); [3]Singh et al. (2018)

4.1.3. Main agricultural polymers and their combustion characteristics

Table 2 shows the most common agricultural plastics that are suitable for technical, mechanical and cost-effective processing:

Table 2. Combustion characteristics of plastics used in agriculture

Name of substance	**Ignition temperature (°C)**	**Heat of combustion (MJ/kg)**
Polyethylene (PE)	350	46.3
Polyethylene terephthalate (PET)	500	22.7
Polystyrene (PS)	470	41.6
Polypropylene (PP)	410	46.6
Polyamide (PA)	500	31.46
Polyvinylchloride (PVC)	760	19.26

Source: Nagy & Kuti (2016)

4.1.4. Utilization of APW

The redistribution of APW is a problem for many governments and waste management researchers (Nagy & Kuti 2016).

Global estimates of agricultural plastic recycling range from 2 to 6.5 million tonnes per year, while in East and Central Asia, the amount of waste produced per year is at least 93 million tonnes (Singh et al. 2017).

In developing countries, disposal waste to landfill continues to be the main method of waste management, which has a negative impact on soil conditions. In addition, the disposal of APW is carried out together with MSW without any sanitary procedures, without processing gas and filters, as these processes involve costs that go beyond economic possibilities (Dianda et al. 2018; Hemidat et al. 2019). For these reasons, there is a large release of methane into the air. Based on data from Anasstasia et al. (2020) approximately 50 Nm^3 of methane is released from one ton of buried waste.

Also, one of the popular recycling methods is open burning of APW on site. Emissions from uncontrolled combustion pollute the air and consist of harmful substances such as carbon dioxide (CO_2) (about 3.40 kg per kg of polyethylene), CO, H_2S, SO_2, NH_3 and dioxin (Scarascia-Mugnozza et al. 2008). This causes the presence of greenhouse gases in the atmosphere that contribute to global warming (Nutongkaew et al. 2014).

A distinctive example is The European Countries: “According to Directive (2006) / 12 / EC of the European Parliament and of the Council of 5 April 2006 on waste, waste landfilling is the least desirable waste management solution in European Union (EU)”. The Figure 3 shows that the main goal of EU circular economy is “turning waste into resource” (Sieradzka et al. 2020).

Recycling in agriculture can be impractical and constitute a financial or a temporary burden for farmers. APW is often an unidentified mixture of various resins and additives - a low-value waste category and may be too low cost to ensure recycling (Nutongkaew et al. 2014). In addition, it may require additional costs for special equipment to dispose of waste from moisture, sand, weed seeds and pathogens, as well as special treatment to remove toxic residues. In this case, non-recycled PW can be intended solely for energy recovery (Bray 2017).

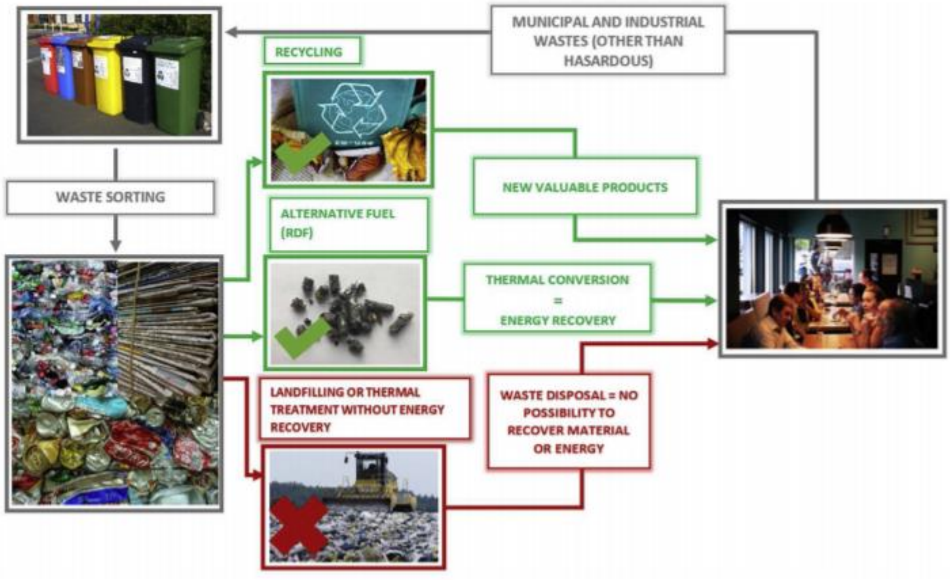

Figure 3. Waste management possibilities = turning waste into resource

Source: Sieradzka et al. (2020)

Of course, there are strategies to increase the lifespan of plastic materials through additives, introduce and stimulate the use of biomaterials (Edo et al. 2016; Bray 2017).

To date, however, a successful solution to minimize pollution is to improve the methods of plastic management and reduce production (Nutongkaew et al. 2014).

4.1.5. APW to energy

Given the increased level of pollution and the large amount of agricultural waste, it is expected that various waste-to-energy processes, including energy recuperation, will play a key role in waste management, as well as in reducing greenhouse gas emissions (Nutongkaew et al. 2014; Nagy & Kuti 2016).

It is possible to produce high-quality refuse derived fuel from solid household waste by shredding, sorting and dehydrating a light fraction, which is then burned and used to produce electricity, ensuring the reasonable use of waste (Zhao et al. 2016; Brás I et al. 2017; Dianda et al. 2018). It is very important for waste management development, particularly in developing countries (Dianda et al. 2018).

This type of fuel can replace fossil fuels (gas, oil, coal) (Thirugnanam & Pragasam 2013) in many areas (especially in industries with high energy consumption), taking into account the principle of proximity producers to consumers (Brás I et al. 2017). The most important of these industries are Power plants, Cement and Iron Smelting factories, Pulp and Paper Milles (Zhao et al. 2016; Hemidat et al. 2019).

An important task is to emphasize the advantages of APW separation, so that they become suitable to produce new recycled materials (Scarascia-Mugnozza 2011; Nagy & Kuti 2016; Vox et al. 2016).

4.2. Refuse derived fuel

4.2.1. Definition

Refuse derived fuel - a flammable fraction produced from industrial and household waste, which includes plastics, biodegradable materials, wastewater sediment, residues from recycling industrial hazardous waste and so on (Gendebien et al. 2003; Diaz et al. 2005; Zhao et al. 2016; Porshnov et al. 2018).

The following definition, described by GAIA (2013), is: RDF is a shredded fuel derived from MSW that does not contain metal, glass or other inorganic materials and whose particles are capable to pass through a sieve with small square cells (Zhao et al. 2016).

There are other terms used to define RDF: recovered fuel (REF), paper and plastic fraction (PPF), packaging-derived fuel (PDF) и processed engineered fuel (PEF) (Gendebien et al. 2003).

4.2.2. Classification of RDF

The American Society for Testing and Materials (ASTM) has established classification standards of RDF that were reapproved in 2006. The seven classifications and their descriptions are summarized in the Table 3.

Table 3. ASTM classification of RDFs

Class	**Form**	**Description**
1. RDF-1 (MSW)	Raw	Municipal solid waste with minimal processing to remove oversized bulky waste
2. RDF-2 (C-RDF)	Coarse	MSW processed to coarse particle size with or without ferrous metal separation such that 95% by weight passes through a 6 in. square mesh screen
3. RDF-3 (f-RDF)	Fluff	Shredded fuel derived from MSW processed for the removal of metal, glass and other entrained inorganics. The particle size of this material is such that 95% by weight passes through a 2 in. square mesh screen.
4. RDF-4 (p-RDF)	Powder	Combustible waste fraction processed into powdered form such that 95% by weight passes through a 10-mesh screen (0.035 in. square)
5. RDF-5 (d-RDF)	Densified	Combustible waste fraction densified (compressed) into pellets, slugs, cubettes, briquettes or similar forms
6. RDF-6	Liquid	Combustible waste fraction processed into a liquid fuel

7. RDF-7	Gas	Combustible waste fraction processed into gaseous fuel

Source: ASTM (2006)

4.2.3. Characteristics and composition of RDF

To characterize and determine the quality of RDF are used the proximate (moisture, ash and volatile contents) and ultimate (C, H, O, N, S contents and HHV) analysis (Dianda et al. 2018).

Quality assurance in RDF production requires fuel to have a HHV and a low concentration of toxic chemicals, especially heavy metals and chlorine (Nithikul 2007).

Since currently the fuel is produced according to the standards of the European Committee, based on scientific research, the heavy metals included in RDF, such as Cd, Cr, Hg and Pb, do not exceed European standards (Nithikul 2007).

Heating value

The total HV of RDF increases as a result of the concentration of combustible components in the composition , which is why the ideal composition of alternative fuels is a high content of plastic (about 37,250 J/g), paper (about 17,460 J/g) or carton, wood and other organic matter (Table 4) (Kara et al. 2008; Brás I et al. 2017).

Inorganic particles (e.g. glass particles) and small wet organic matter (e.g. cooking waste) make up a fraction with a relatively lower heating value (LHV), i.e. about 10,800 J/g. The inclusion of the latter category in RDF can reduce the overall HV of RDF by about 20%.

Table 4. HV of plastic materials, paper and wood

Materials	**HV (MJ/kg)**
Polyethylene	46.0
Polystyrene	46.0
Polyvinyl chloride	18.9

Paper and wood	16.0 – 16.8

Source: Brás I et al. (2017)

Table 5 presents the percentage of RDF compositions that are mostly used in production and have the necessary combustible components in their composition.

For example, I chose indicators of developed and developing countries:

Table 5. Typical RDF composition in %

	[1]Belgium	**[1]UK**	**[2]India**	**[3]Thailand**
Plastic	31	11	13	16
Paper / cardboard	13	84	12	12
Wood	12	5	-	11
Textile	14		3	3
Organic degradable waste	30		25	35
Undesirable material (glass, stone, metal)	-		4	23
Yard waste	-	-	43	-

Source: Author, based on [1]Gendebien et al. (2003); [2]Sheth (2016); [3]Srisaeng et al. (2017)

Moisture

Another important advantage of high-quality fuel is a lower moisture content compared to the original APW data. This benefit is particularly important in the case of developing countries, where garden waste and food usually have a high concentration of wet rotten matter, compared to, for example, paper.

It should be noted that the content of PW does not affect this characteristic, since they have very low rates (Table 6) (Zhao et al. 2016).

Volatile matter

Gaseous and vaporous products released during the heating of fossil fuels under standard conditions are called volatiles. They are formed as a result of thermal decomposition of fuel (Porshnov et al. 2018).

A research conducted in Singapore (Zhao et al. 2016) shows that plastics (PP/PE, PET, PS) contain a very high percentage of volatiles (Table 6).

Table 6. Proximate analysis of waste components

	Moisture (%)	**Ash content (%)**	**Volatile matter (%)**
PP/PE	0.06	0.03	99.4
PS	0.12	0.02	99.8
PET	0.5	0.1	94.6
Textile	5.4	0.9	93.6
Landfill mining materials	21.2	8.1	63.3
Paper	7.1	17.1	75.6
Horticulture	45.3	2.7	46.5
Chicken manure	16.3	34.3	51.4
Biomass waste	73.8	1.1	21.4

Source: Zhao et al. (2016)

4.2.4. Comparison with MSW and coal

The estimated energy recovery potential of RDF, MSW and Coal incineration are shown in Table 8. Based on data from the table, it can be concluded that RDF has qualities:

- a sufficiently high rate of HV, in contrast to MSW

  (HV of pellets 14,650-16,750 kJ/g - this is equivalent to E class coal)

- low moisture content

  (RDF can potentially have 15-25% lower than the original waste. Also, there is example from India where moisture content of RDF is 10% and coal has whole 39% (Thirugnanam & Pragasam 2013))

- ash content is twice as low as comparing to MSW

  (This is responsible for lower emissions of pollutants into the atmosphere)

Given the characteristics of fossil fuel (Table 7), RDF has good data and moreover, alternative fuel is three times cheaper and costs about $27 per ton. Of course, the indicators vary depending on different factors: location, climate, waste, and the process of collection and processing (see 4.2.5 for more details).

Table 7. Comparison of important fuel properties

	RDF	**MSW**	**Coal**
HV (kJ/g)	12,000-16,000[1] 15,000-20,000[5,6] 14,600-15,500[3]	11,000-12,000[1] 8,000-11,000[7] -	21,000-32,000[1,2] - 16,700[3]
Moisture content (%)	< 20[5] 10[3]	30-40[1]	3 – 12[1,2] 39[3]
Ash content (%)	10-22[1,5,6] < 15%[3,4,5]	25-35[1]	5-10[1,2] 4.2[3]

Source: Author, based on [1]Diaz et al. 2005; [2]Khairil et al. 2012; [3]Thirugnanam & Pragasam 2013; [4]Zhao et al. 2016; [5]Paramita et al. 2018; [6]Hemidat et al. 2019; [7]Azam et al. (2020)

Raw MSW has high moisture content, LHV (Zhao et al. 2016), a wide range of granulometric composition and high ash content. These reasons make the use of MSW as fuel difficult and unattractive.

The main advantages of RDF over MSW are HHV (which remains quite constant), greater homogeneity of physical and chemical compositions, lower emissions of pollutants (Caputo & Pelagagge 2002; Nithikul 2007).

In Indonesia, the study was conducted that obtained the following data on RDF composition (Table 8). This data compared to low-grade coal and charcoal characteristics (Dianda et al. 2018):

- moisture content and volatiles in RDF are lower
- ash content of RDF is higher
- HV of RDF is higher

Table 8. Comparison with coal and charcoal

Fuel type	**Moisture content**	**Volatile content**	**Ash content**	**HV (MJ/kg)**
Coal	11.82	46.61	3.54	22.38
Charcoal	6.8	48.13	3.91	23.91
RDF	6.4	8.82	9.2	24.96

Source: Dianda et al. (2018)

4.2.5. Manufacturing process of RDF

To date, many different variants of the RDF manufacturing process have been developed and each of them has certain characteristics, advantages and disadvantages (Gendebien et al. 2003; Diaz et al. 2005; Kara et al. 2008).

For example, Figure 4 shows a typical installation diagram. With this design, it is possible to recycle 500 to more than 2,000 tonnes of waste per day (Williams 2005).

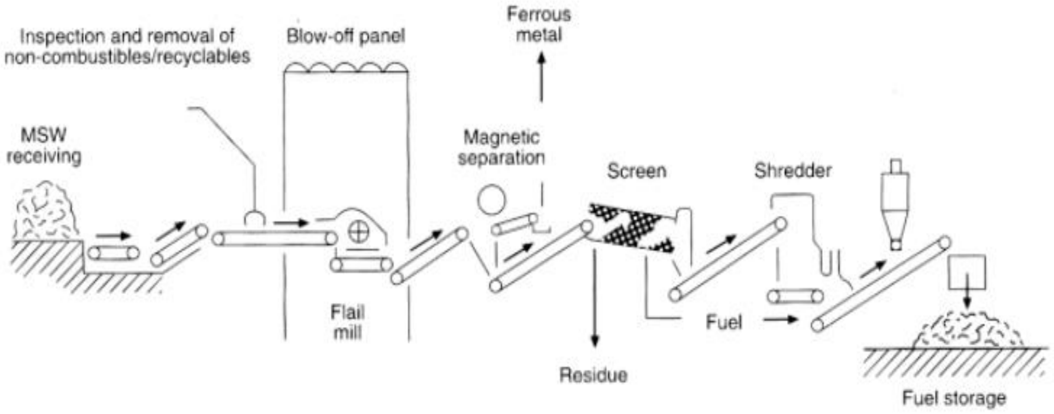

Figure 4. Schematic flow sheet for a typical RDF manufacturing process

Source: Williams (2005)

This is how the plant concept of fuel production looks like in practice (Figure 5):

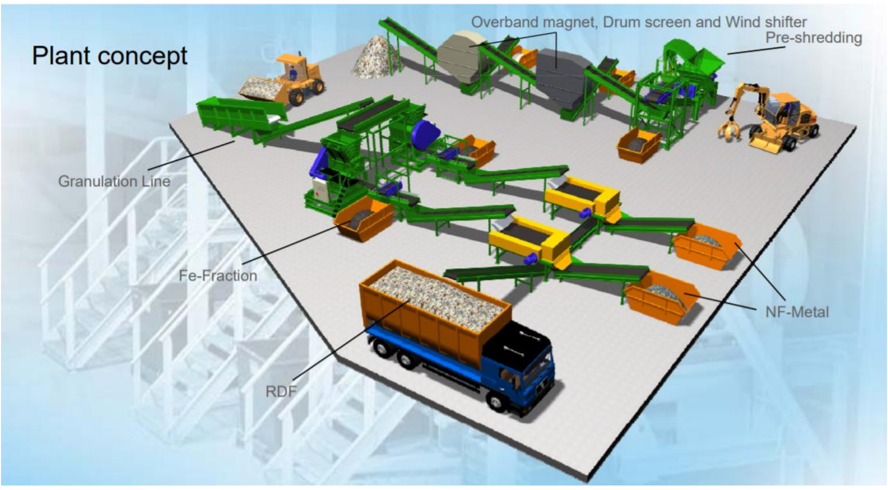

Figure 5. RDF plant concept

Source: BiomassPelletMachine (2020)

Most often, the RDF production process is divided into two subsystems – front end (pre-processing) and back end (process of conversion). The front end system is designed to receive and sort waste into combustible and non-combustible fractions. Back end system deals with thermal or biological waste treatment (Gendebien et al. 2003; Diaz et al. 2005).

At the initial stage of waste treatment, it is important to reduce the moisture by drying it in the sun, spreading it evenly over an open asphalt surface. The duration can be from 1 to 2 days (Sheth 2016).

Production line of RDF consists of several sequential steps that separate unwanted components.

The main operations of the whole process are:

- separation – manual, mechanical;
- size reduction;
- screening (pre-trommel screening);
- density separation – air classification;
- shredding metal, glass or wet organic materials;
- drying
- densification - pelletization.

Depending on the waste input and the requested RDF quality, the operations listed above may vary and occur in different sequences or not at all (Caputo & Pelagagge 2002; Porshnov et al. 2018).

In India, for example, the fuel production process is as follows:

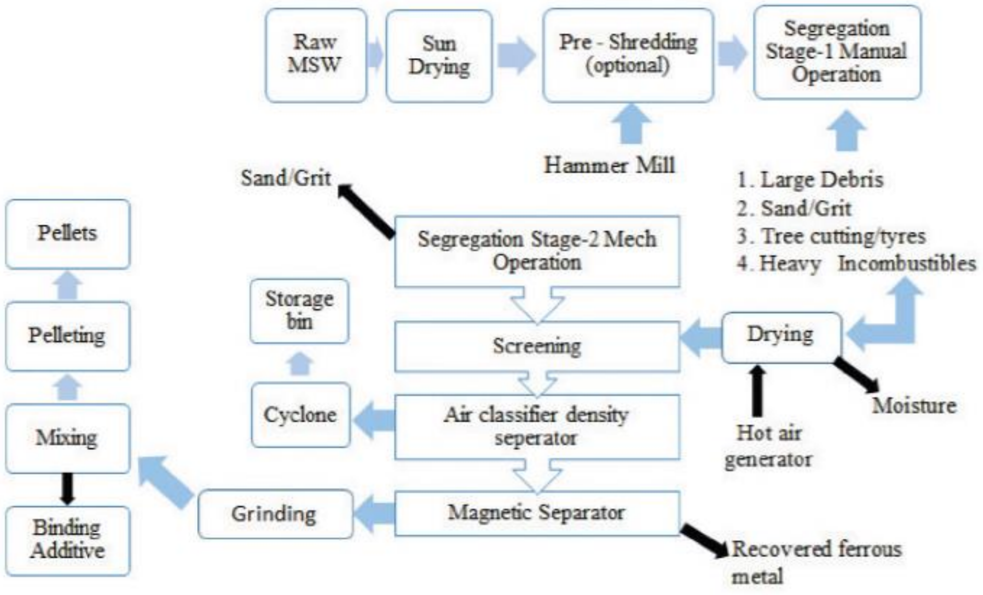

Figure 6. Production process of RDF

Source: Sheth (2016)

Manual separation

First of all, workers (sorters) may face the presence of oversized items (household appliances, furniture, construction debris) or hazardous, polluting substances in the total mass of mixed waste. Such waste is often manually disposed before mechanical processing to minimize the occurrence of further pollution and mechanism failures (Diaz et al. 2005).

For the process of manual separation is usually used a table or sorting tape, which is shown in Figure 7.

Figure 7. Sorting belt

Source: BobruiskaGromach (2020)

Mechanical separation

This phase of waste treatment most often involves the processes that are listed and described below:

Size reduction

The term "size reduction" in the waste management – is a process in which the particle size of solid waste is made smaller (CollinsDictionary 2020). It is also commonly known as "shredding" and "grinding". But there is a difference between terms: shredding is used for size reducing mixes waste, grinding is sometimes used for glass (Anasstasia et al 2020).

Size reduction occurs by a hammer mill or shredder (Sheth 2016). This allows to create a kind of homogeneity - to transform large objects into particles whose size (approximately 10cm) will meet the stated requirements for the correct functioning of technological equipment (Khoo 2019).

Secondary and tertiary shredding to less than 10 cm may be required for higher quality RDF production. This phase is therefore very important in the mechanical treatment of mixed waste and requires special attention (Sheth 2016).

Screening

The main goal of screening is to achieve an effective size separation. This process leads to the segregation of feed stock into two types of fractions – oversize (hold on the screen) and undersize (passed through the screen). The removal of small particles reduces ash content (Anasstasia et al 2020).

The industry mainly uses two types of screen:

- Trommel screen

Trommel is inclined downwardly, rotary, cylindrical screen. Due to the presence of a mesh, it is able to deal with complex flat particles of plastic, paper or crushed glass (Sheth 2016).

- Disc screen

Disc screen is used for separation of inorganic materials from RDF fractions, from paper materials and from wood waste. It consists of shafts in a horizontal plane with discs. There are holes between the disks that allow small particles to penetrate. When the shafts are rotated, the waste is transferred from one end to the other. The tumbling is less rigorous than that obtainable with a trommel screen (Diaz et al. 2005).

Air classification

The process by which materials are divided into categories by aerodynamic characteristics is called air classification. Air classification is used to separate light fraction - organic material from heavy fraction - inorganic material (Sheth 2016). These characteristics are determined by size, geometry and density. The process is based on interaction between moving stream of air (Figure8), shredded wastes and gravitational force: “air classified light fraction” – suspended fraction (paper and plastic materials), “air-classified heavy fraction”– settled fraction (glasses) (Diaz et al. 2005).

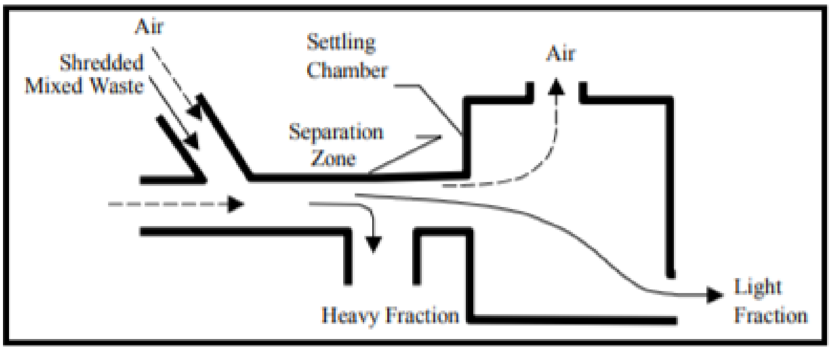

Figure 8. Horizontal air classifier

Source: Diaz et al. (2005)

Magnetic separation

According to Zong et al. (2018), in order to segregate ferrous (magnetic) metal from a mixture of different types of materials such as plastic containers, glass or some another mixed waste, there is technically simple and of relatively low cost method called „magnetic separation“.

The process consists of three main parts: magnetic head pulley, drum, and magnetic belt (Figure 9).

The material to be sorted passes through the first point - magnetic head pulley, where the magnetic particles accumulate around the rotating pulley and the non-magnetic particles follow to the next step (Diaz et al. 2005).

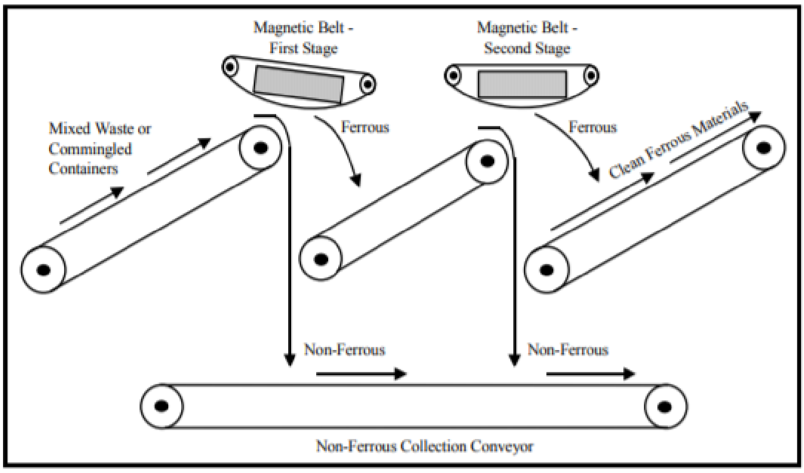

Figure 9 The process of magnetic separation

Source: Diaz et al. (2005)

Drying and densification or pelletizing

In production of RDF, special attention is paid to the process of drying and densification, because it helps improve the quality of fuel. After magnetic separation, binders, such as calcium hydroxide, are added to the RDF particles (Thirugnanam & Pragasam 2013).

Densification is used for production of densified-RDF by way of briquetting, pelletizing, or cube formation with size usually 30mm (Kara et al. 2008). RDF pellets are relatively loose and can be stored and used in the same way as charcoal (Anasstasia et al 2020).

Figure 10. Briquets of RDF

Source: PowerMax (2019)

To successfully obtain high-quality fuel, the exact sequence of the above processes, use the equipment correctly, and carefully to conduct primary sorting must be respected (Anasstasia et al 2020).

4.2.6. Application of RDF

The practice of burning RDF is already quite common among the member countries of the International Energy Agency (IEA) and the International Solid Waste Association (ISWA) and, moreover, is gaining growth in development (Surroop & Mohee 2011). RDF is actively used for cement kilns, power plants, coal-fired power plants, pellet stoves, industrial steam and heat boilers (Nithikul 2007).

However, in developing countries, it is currently common secondary fuels from mainly 2 industrial sectors, that are described below.

There are emission standards which have important aspect when using RDF. Different emission standards are applied for different industries as shown in Table 9.

Table 9. Emission standards for different industries

Parameter	Coal Fire Power Plants	Cement Kilns	Coal Boiler Industries	Biomass Boiler Industries	Municipal Waste Incinerator*	German Waste Incinerator
SO_2 (ppm)	700	50	700	60	30	50
NOx as NO_2 (ppm)	400	600	400	200	180	200
Particulate (mg/m^3)	320	300	320	320	120	10
HCl (ppm)	N / A	N / A	N / A	N / A	25	10
Dioxin (ng/m^3)	N / A	N / A	N / A	N / A	30	0.1

*Capacity > 50 ton / d

Source: Nithikul (2007)

Table 9 shows that the emission standards for MSW incinerators are the most stringent. In addition, HCl and dioxin standards are only used for combustion and are not applicable for other industries (Nithikul 2007).

4.2.6.1. Cement industry

The Cement industry is one of the world's largest energy consumers, with a share of 12-15% (Paramita et al. 2018). Coal, oil and natural gas are the main fuels used in this field. However, in recent years, low-quality fuels have been increasingly used: shale, coal washing, petrol coke, waste oils, solvent, tires, as well as bone meal and animal fats (Gendebien et al. 2003).

The cement industry produces 5-7% of CO_2 emissions. However, some studies indicate that these rates have declined by about 5% globally in recent years as a result of increased energy efficiency and the use of alternative fuels (Gendebien et al. 2003; Hemidat et al. 2019).

Conditions in cement kilns are very favorable for the use of RDF: the combustion process takes place at very high temperatures, there is an oxidative atmosphere and alkaline environment, sufficient time for hazardous waste disposal (more than 2 seconds), while all metal and non-metal combustion products are completely absorbed (Kara et al. 2008).

The use of RDF as a fuel substitute for the cement industry is cost-effective if: there are no restrictions on recycled waste, RDF products are sold to the cement industry and the price of RDF products is cost-effective (Anasstasia et al 2020).

Preferably, the production of RDF is the result of bio-dried waste fractions with a particle size of more than 45 mm, which are mainly composed of plastics and paper, and its use in the cement industry will be reasonably appropriate (Paramita et al. 2018).

In many European countries, cement industries cover more than 70% of total energy consumption through the use of RDF (Schwarzböck et al. 2016).

4.2.6.2. Power generation

According to Thirugnanam & Pragasam (2013) from 750 tonnes of waste 192 tonnes of RDF are generated. With this amount of finished fuel, it is possible to produce up to 7.5 MW of electricity while significantly reducing dependence on fossil fuels.

Figure 11 details the process of generating electricity with RDF.

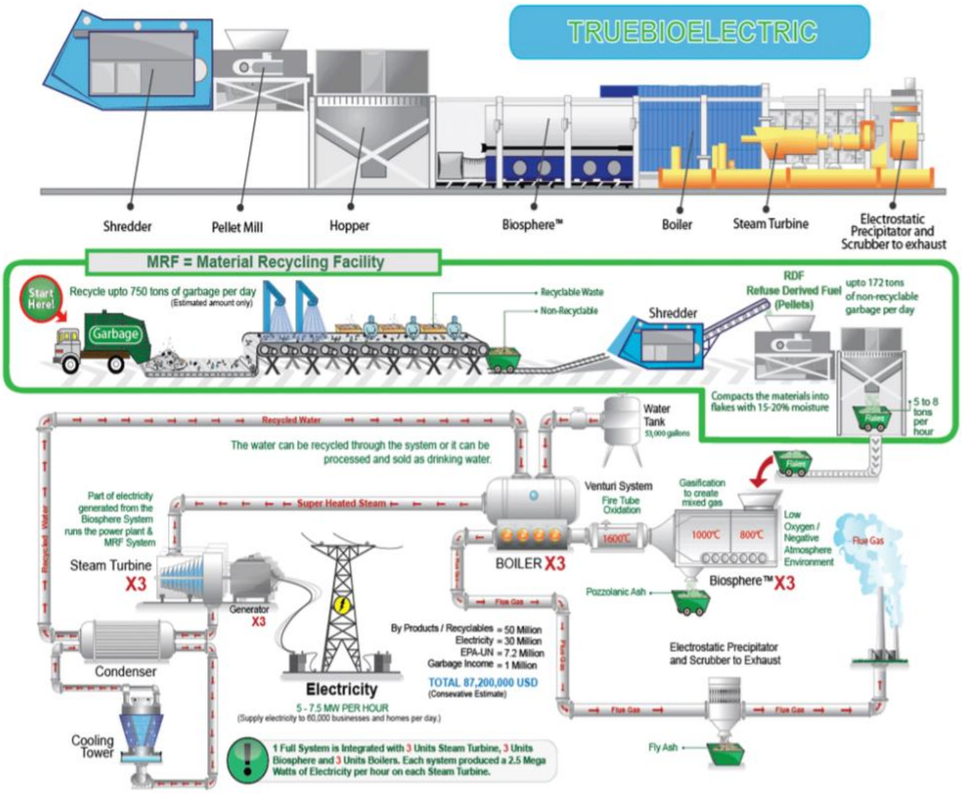

Figure 11. Production of electricity from RDF

Source: Thirugnanam & Pragasam (2013)

Despite the fact that coal is a necessary fuel in all power plants, the use of fossil fuels has many problems: there are emissions of flue gases containing sulfur, and careful ash treatment is also required (Gendebien et al. 2003).

In this case, the RDF with its characteristics is a good substitute.

The quality of the alternative fuel used depends on the type of power plant. For example, a coal-fired power plant requires a higher quality RDF than a power plant that uses brown coal (Nithikul 2007).

4.2.7. Merits and demerits of RDF

After analyzing data from various studies, it is possible to sum up and show the main advantages and disadvantages of the production and use of alternative fuels (see Table 10 below).

Table 10. Merits and demerits of RDF

Merits	Demerits
• Ability to "compose" input from a wide range of wastes (the better the composition, the better the fuel) • Easy-to-reach fuel transportation • Long-term storage of the finished product • Has a beneficial effect on CO_2 emissions to the atmosphere due to low ash and sulphur content • More uniform composition contributes to uniform combustion • Low moisture content contributes to HHV • Simplicity of processing and low production costs • Provision of heating, electricity generation and waste management • Lower cost than coal • Worthy alternative to fossil fuels • Ability to supply and feed RDF continuously	• Serviceable equipment required; process carefully monitored • Some stages of production depend on weather conditions • Fuel quality depends on the processing steps and this leads to additional costs • Significant chloride content, which during combustion may cause corrosion on the inner surfaces of the mechanism • Many toxins are not destroyed during combustion (dioxins and furans) and are released into the atmosphere

Source: Author according to Diaz et al. (2005); Caputo & Pelagagge (2002); Kara et al. (2008); Thirugnanam & Pragasam (2013); GAIA (2013); Nutongkaew et al. (2014); Kungkajit et al. (2015); Nagy & Kuti (2016); Zhao et al. (2016); Sheth (2016)

4.3. RDF technology adoption process in developing countries

In order to describe the full potential of RDF in developing countries, the following aspects of sustainability need to be considered:

- Economic (value of finished product)
- Social (analysis of society's perception of waste sorting and collection)
- Environmental (avoided GHG emission and CO_2)
- Technical (production process quality = fuel quality)

Sustainability can only be achieved if all aspects are implemented (Paramita et al. 2018, Khoo 2019).

4.3.1. India

According to Kubota & Ishigaki (2019) for 2012, there are active 29 plants in India that produce RDF and 8 waste to energy (WtE) plants.

Sheth (2016) noted that production of RDF is about 210 Mt/d as fluff and pellets. Produced fuel may be able to support 88 power plants with capacity of 5MW for 5-7 years. RDF corresponds to the minimum HV (20,000 kJ/g) and can be used as an additional fuel for the main combustion process in the cement industry.

In the Report of European Planning Commission (2003), it was observed that the volume of MSW in the country has a potential to produce 32,890 tonnes of RDF per day.

Solid Waste Management Rules (SWMR) requires manufacturing plants to replace fossil fuels with at least 5% of total fuel consumption (Kubota & Ishigaki 2019). Also, for speeding up the process of WtE, planning commission invited to divide waste among the cities and implement the waste-to-energy technology.

4.3.2. Indonesia

According to the Decree of the Ministry of Environment and Forestry, since 2012 RDF has been included for use as a substitute for fossil fuels (Anasstasia et al 2020). In 2016 RDF production and recycling guidelines for the cement industry were published (Kubota & Ishigaki 2019). On the Figure 12 is shown how RDF production increased between 2009 and 2016 (Anasstasia et al. 2020).

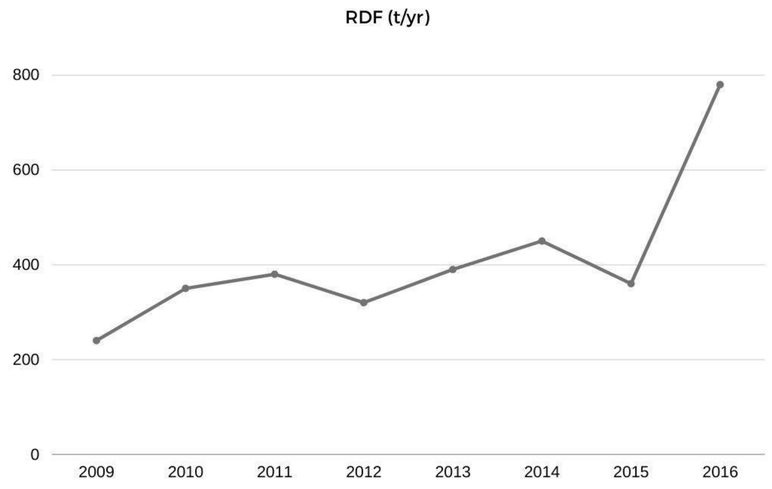

Figure 12. The annual production of RDF

Source: Author, based on Anasstasia et al. (2020)

In Indonesia, the cement industry uses third-class fuel - Fluff RDF, which has a HV of approximately 17 MJ/kg and higher (ASTM 2006; Anasstasia et al 2020). Production cost of RDF is in the range of 18-19$ per ton, which corresponds to the prices of rice husks, which also periodically replace fossil fuels (Paramita et al. 2018).

Paramita et al. (2018) noted that due to the production of RDF, the prevention of GHG emissions is 6,000 Nm_3/ton landfilled waste per day or 2,190,000 Nm_3/ton of waste per year, which is about 1.3% of the country's total greenhouse gas emissions (Schwarzböck et al. 2016).

Also, in Indonesia it is possible to replace about 58% of conventional fuels. This will reduce CO_2 emissions from cement plants by about 3.6 million tonnes per year (Paramita et al. 2018). Another study of the use of RDF in the city of Gresik suggests that the cement company uses alternative fuels and replaces 30% of the total coal use by RDF (Kubota & Ishigaki 2019).

The problem in Indonesia is that most cement plants are located on the island of Java. In this case it is necessary to solve convenient, fast and financially affordable transportation of finished fuel to consumers (Schwarzböck et al. 2016).

4.3.3. Thailand

According to the studies of Kubota & Ishigaki (2019) as for 2016 in Thailand were 15 municipalities producing RDF. Due to the increase in coal prices, cement companies are interested in using RDF as an additional fuel and are willing to use RDF at 40% substitution (energy base), which is about 2.7 million tonnes of RDF per year. While the potential production of RDF in the country is about 2.46 million tonnes / year (Gendebien et al. 2003).

A study by Nutongkaew et al. (2014) found that RDF-5 or densified fuel could be produced in the country. Its composition is a mixture of plastic - 50%, paper - 16%, palm kernel - 17% and limestone - 17% (Figure 13). The RDF's HV is expected to be 21,000 MJ/t, with a moisture content of 60% and greenhouse gas emissions of approximately 1,423 - 1,696 kg of CO_2.

Figure 13. The materials used in RDF-5 preparation

Source: Nutongkaew et al. 2014

5. Conclusions

Nowadays a large amount of information related to APW suggests that the issue of the possibility of proper recycling of PW, especially in agriculture, is being raised with increasing frequency. Combined with renewable energy policies, RDF can significantly improve the environment.

Besides reducing GHG and CO_2 emissions to the atmosphere, its advantages also include reducing economic losses in certain regions. Using RDF, it is possible to conserve fossil fuels and improve the energy security of developing countries.

To date, unfortunately, it is impossible to produce fuel that has no negative impact on the environment. It is important to continue the detailed study of the physical and chemical characteristics of the RDF components in order to produce a more environmentally friendly product. This requires the development of new fuel processing and production technologies, such as embedded filtration systems. It is also necessary to share knowledge among equal countries in the field of modern technology.

In order to stimulate the production and use of RDF in developing countries, it is necessary to create laws that will include financing for proper waste management. On the government side, it is necessary to coordinate the participation of stakeholders: farmers, waste management municipalities, producers of RDF and consumers.

Moreover, the social dimension should be considered. It is necessary to take into account the interests of workers, create good working conditions and arouse interest in conscientious work.

The development of this industry is just beginning to spread, but I am sure that this is already a big step towards the green environment.

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