



Assessment of the Energy Potential of Plastics as a Component of ANFO-type Explosives

Jolanta Biegańska

Department of Hydrogen Energy, Faculty of Energy and Fuels, AGH University of Krakow, Poland

<https://orcid.org/0000-0003-2356-3247>

corresponding author's e-mail: biega@agh.edu.pl

Abstract: Many methods have been developed to reduce the environmental impact of plastic waste. New technologies have been developed to make high-temperature utilisation of these wastes possible. A promising method for the unconventional disposal of plastics by detonation was identified. The popular explosive ANFO (Ammonium Nitrate Fuel Oil) is a component mixture of oxidiser (ammonium nitrate) and fuel (diesel fuel). The optimal composition is 94.5% oxidiser and 5.5% fuel – a guarantee of complete and total combustion. Plastics have a chemical composition and oxygen balance similar to fuel oil. It is possible to replace the fuel share in ANFO by adding plastics and using the energy they contain. The amount of energy that can be recovered is high for PE and PP (at the level of 0.6) and PS – 0.5. Using polymers as ANFO components is advantageous for economic reasons – plastic waste will be eliminated during blasting works.

Keywords: energy potential, waste plastics, ANFO

1. Introduction

Plastics have been a useful material used in many industries for many years. Approximately 90% of the overall demand for this raw material is met by low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), polyethylene terephthalate (PET), (polyvinyl chloride) PVC and (polystyrene) PS (Rodrigues et al. 2019).

After the use stage, plastics become waste, and then they are left to be (Mutha et al. 2006, Kuczynski & Geyer 2010, Geyer et al. 2017):

- recycled or reprocessed,
- subjected to thermal disposal (waste-to-energy),
- landfilled.

According to the OECD (OECD 2022), 353 million tonnes of plastic waste was generated globally in 2019, of which only 9% (33 million tonnes) was recycled. According to the OECD scenario, with this waste increasing to 1014 million tonnes by 2060, landfilling will remain the common form of disposal. Compared to other methods, this way of disposing of plastics is projected, as shown in Figure 1.

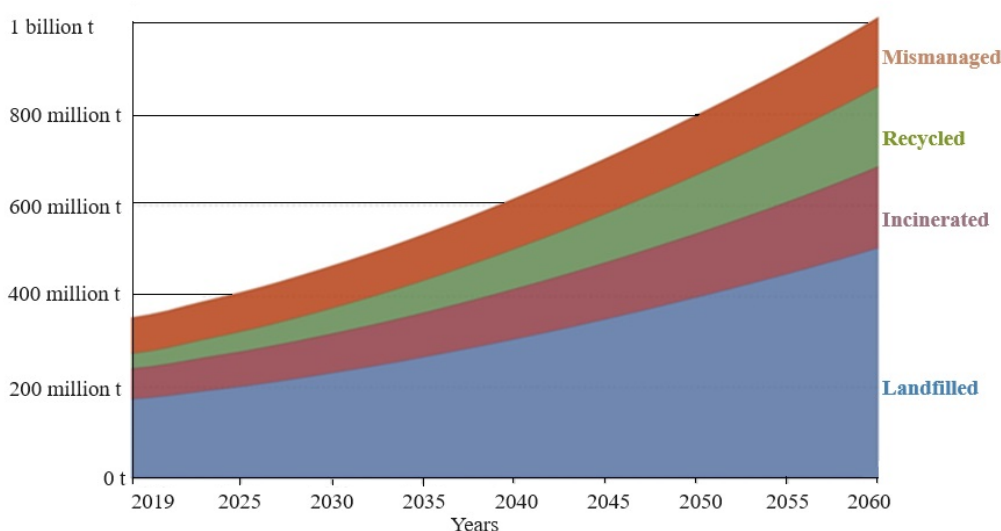


Fig. 1. Projections of plastic waste by disposal method, World (Ritchie et al. 2023)



A similar scenario presents itself for Europe, but in this case, landfilling and incineration are equivalent disposal forms.

Due to the high durability of plastics and the negative environmental impact if left as waste, various management/disposal methods are being developed.

Attention is drawn to the high energy potential contained in these materials, comparable to fossil fuels (coal, oil). Therefore, the case for using plastics and, at the same time, disposing of them in thermal processes is not unexpected.

Attempts have also been made to use these waste substances as components in explosives/blasting materials (BM) (Biegańska et al. 2004, 2005, Biessikirski et al. 2021).

One of the most commonly used explosives (BM) for rock mining in open-pit mines is ANFO (Ammonium Nitrate Fuel Oil) (Mining..., 2021, Global ANFO 2023). It is also used in metal ore mining and construction (tunnelling and demolition). Regarding industrial use, this material has the largest market share at 56%. ANFO's properties, such as safety, low price, and simple production process, favour its widespread use. It was found (Oluwoye et al. 2017) that the optimal composition of ANFO is 94.5% ammonium nitrate and 5.5% fuel oil. When detonating such a mixture, the formation of toxic gases is minimal; ideally, no products that pose a risk to health and safety should be produced.

2. Disposal Methods for Plastics

Reducing plastic waste is the most effective way to clean up the environment. Proper waste management and source reduction is one of the possible steps to achieve this goal. Only some of the many techniques for managing this waste (recycling, landfilling, incineration and bioremediation) have a scientific basis (Pan et al. 2020). Figure 2 illustrates the different methods used to manage plastic waste and shows the new technologies increasingly being implemented.

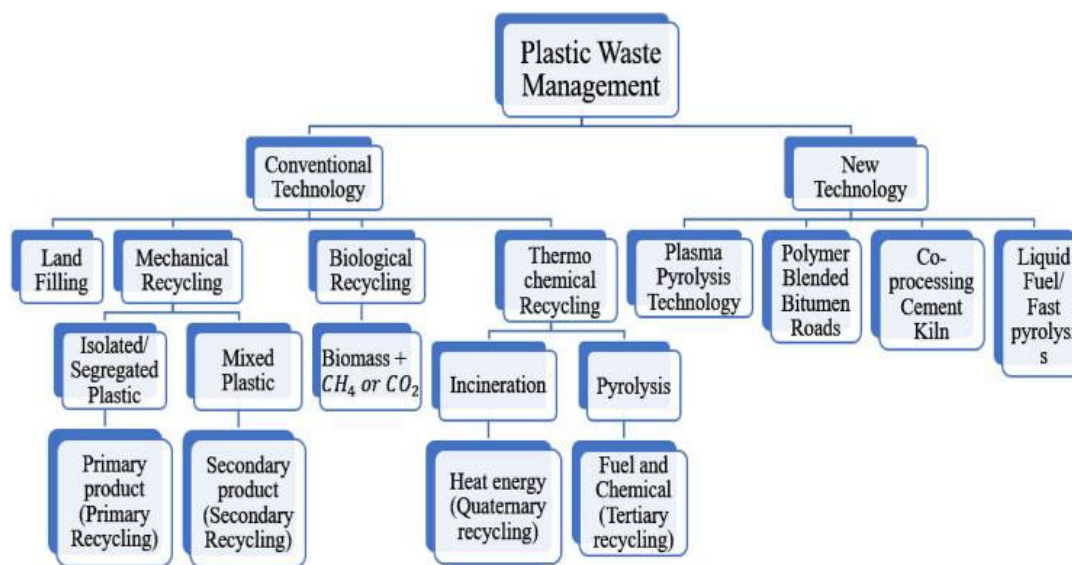


Fig. 2. Different routes for plastic waste management (Kibria et al. 2023)

It has been noted (Garforth et al. 2004) that landfilling polymer waste is an environmental hazard (this type of waste is poorly biodegradable). Their degradation rate is very slow – for most plastics, the half-life is hundreds or thousands of years once buried in the ground. Only LDPE bags have a short half-life – they decompose in 4.6 years (Chamasa et al. 2020).

Much of this waste is in the municipal waste group; therefore, this form of disposal requires additional efforts to operate landfills properly. As can be seen from the diagram in Figure 2, studies are moving towards developing other forms of disposal for this waste.

2.1. Conventional technologies

In this group of methods, the reuse of post-consumer plastics in various forms of recycling (mechanical, biological and thermochemical) is favoured.

Some types of plastics, after preliminary purification, are crushed and – in powdered form – are used as additives in various products (Gao 2002, Song et al. 2012, Briassoulis et al. 2013, Bilewicz et al. 2014, Wucher et al. 2014, Chen et al. 2019, Titone et al. 2024).

It is the simplest form of recycling but requires an energy input for treatment, sorting, transport and processing. Biological recycling is breaking down plastics into simple substances using microorganisms.

After such processing, the simple substances will integrate (reintegrate) into the natural environment. It is a time-consuming form and requires the selection of bacteria, fungi and similar microorganisms dedicated to specific types of plastics (Shah et al. 2008, 2016, Al-Salem et al. 2010, Fei et al. 2018, Bandopadhyay et al. 2018, A Hosni et al. 2019, Siracusa 2019, Yuan et al. 2020, Chaurasia 2020, Mohanan et al. 2020, Dailin et al. 2022).

The thermochemical recycling method uses various steps to convert plastics to low molecular weight chemical products (Rahimi & García 2017, Garcia & Robertson, 2017, Zeller 2021). They have further applications, and the processes of such recycling are pyrolysis, gasification, thermal cracking and various forms of incineration (López et al. 2010, Bujak 2015, Uekert et al. 2018, Huang et al. 2018, Nanda & Berruti 2021, Maslak 2021). Using the right equipment (suitable combustion chambers, control systems, flue gas treatment systems), this form of plastic conversion allows energy to be recovered in an environmentally safe way. It can be financially profitable (Scott 2007, Eriksson & Finnveden 2009, Thanh et al. 2011).

It was concluded (Hahladakis et al. 2018, Gharde & Kandasubramanian 2019) that thermal decomposition is an important means of chemical recycling of waste plastics – low pollution of the atmosphere, high product utilisation and high value.

2.2. Modern technologies

The state-of-the-art methods include plasma technologies, polymer-modified road asphalt production, pyrolysis and co-firing in a cement kiln.

Plasma pyrolysis is an innovative thermal technology (Pragnesg et al. 2010, Punčochářa et al. 2012), in which plastic waste is converted to simple substances at high temperatures (approx. 1727°C to 9727°C) from 2,000K to 10,000K (under almost anaerobic conditions) with the production of a valuable gas (syngas). It contains simple molecules of CO, H₂, CH₄ and higher hydrocarbons in small amounts. To increase gas production, argon plasma (in the form of vapour) was used (Sekiguchi & Orimo 2004). It has proved particularly useful for converting PE in granular form.

Hot plasma can be used to destroy toxic substances and is useful for the disposal of plastics containing chlorine – mixed waste can also be disposed of in this way (Smriti et al. 2016). This technology's suitability for destroying waste multilayer plastics has also been demonstrated (Bhawan & Nagar 2016).

Studies have been conducted on the decomposition of plastics using different pyrolysis methods (Slapak et al. 2000, Pionto et al. 2002, Orgianni et al. 2002).

A steam gasification process was designed for PVC plastics. A variation of this process, fluidised bed gasification, was used, where the temperature of the process played a significant role in the gas composition.

An interesting application of plastics was found to improve the rheological properties of asphalt. The addition of plastics to the asphalt mass resulted in, among other things, higher durability and moisture resistance in the final product (Sabadra 2017, Sulyman 2017, Janik et al. 218). On the other hand, the addition of shredded polyethylene bags and aggregate (Kazmi & Rao 2015) has worked well as a binding agent in road construction.

Research has been conducted (Joohari & Giustozzi 2020, Joohari 2021) to increase the durability of asphalt using a hybrid polymer – elastomer and plastomer. This combination proved a good solution (the high temperature did not affect the phase separation between polymers and asphalt).

Plastic waste has also been used as fuel in cement production in co-processing cement kiln technology (Poddar & Paranjpe 2015, Baidya et al. 2016, Ghosh & Ansari 2019, Prakash & Palkar 2023). The research aimed to recover the energy contained in plastics and simultaneously dispose of them in an environmentally friendly manner. Co-firing of polyethylene waste (with coal or petroleum coke) in cement kilns allows partial replacement of conventional fuels and has no negative environmental impact. The temperature in the cement firing process ranges from 1,123.15K to 2,073.15K (850°C to 1800°C), allowing the plastics to burn completely without forming harmful gases. The products of the process are NaCl, KCl and CaSO₄. It was also found that such a process has no negative effect on the properties of the clinker.

It has been shown, using the so-called discrete dynamic programming (Amsaveni et al. 2020), that, in the cement industry, plastics are a raw material that can be maximised through co-processing.

Life-cycle assessment studies (Cement 2021) have shown that this is a better alternative than storing and incinerating plastics. In India, several plants have been set up that specialise in processing waste plastics in such processes (Ultra Tech 2021). In Japan, investments are also being made to build plants for greater use of waste plastics in the process mentioned above (Compendium of Technologies 2021).

In the group of modern technologies, a variant of pyrolysis leads to the production of liquid fuel from waste plastics. Ultra-fast pyrolysis (flash pyrolysis) is an extremely fast thermal decomposition whose main products are gas and bio-oil. The heating rate can range from 100 to 10,000°C/s, and the residence time of the waste in the reactor is short – a few seconds (Eze et al. 2021).

Various facilities for so-called fast pyrolysis have been studied in detail, using the following waste for this purpose: PP, PS, and PET (Namkung 2022). The quality of the oil obtained was in accordance with government regulations (in this case, the Korean ones) where the work was carried out.

Different reactor designs were developed to improve the efficiency of the pyrolysis process (Ahamed et al. 2020, Sharma et al. 2022). A parallel study (Aisien et al. 2021) was carried out to compare thermal and catalytic pyrolysis. It was found that thermal pyrolysis yielded a maximum liquid oil content of 83.3 wt.%.

Microwave-assisted continuous pyrolysis (Zhou et al. 2021) proved an interesting approach, with the highest liquid product yield obtained at 833.15K (560°C).

Thermolysis, as a special case of pyrolysis (Panda et al. 2010, Idumah 2022), has been used successfully to obtain liquid oil – the need for its purification was highlighted. This product could be a future fuel alternative.

3. The Energy Potential of Plastics

Among the methods discussed for the disposal of plastics, various forms of incineration are highlighted as a radical way. Thermal methods allow energy recovery, i.e. the use of waste with a high energy value, which also fits into the hierarchy of waste management and the Zero Waste concept (EU 2008, Cole et al. 2014).

3.1. Net calorific value of plastics

The thermal properties of a substance's suitability for energy recovery are determined by its chemical composition, and the most important quantities characterising the amount of heat generated in the combustion process are:

- heat of combustion – HHV (High Heating Value): the amount of heat given off by the complete and total combustion of a unit quantity of fuel after cooling the gaseous products to the initial temperature of the substrates and condensing the water vapour from the flue gases,
- net calorific value – LHV (Low Heating Value): the difference between the heat of combustion and the heat of vaporisation of water released from the fuel during combustion; the net calorific value is lower than the heat of combustion by the amount of the heat of condensation of the water vapour contained in the flue gas.

Plastics are a favourable energy source due to their high calorific value. According to estimates (Vilanova & Eder 2014, Stegmann et al. 2022), the average LHV for plastics is 35 MJ/kg. This is derived from the average value of this parameter calculated, based on literature data, for each type of plastic multiplied by its global market share.

It was assumed (Geyer et al. 2017) that the global market share of each plastic type is for:

- PP 19%,
- LDPE 18%,
- HDPE 15%,
- PP&A (polyester, polyamide and polyacrylic) 14%,
- PVC 11%,
- PET 9%,
- PU (polyurethane) 7% and
- PS 7%.

Based on literature data, the following LHVs (lower heating values) for the different types of plastics have been determined (Table 1).

Table 1. Average lower heating values (LHV) per plastic type

Polymer	Calorific value LHV* MJ/kg	LHV** MJ/kg	Reference
Polyethylene (PE)	43.3	43.35	(Chielini & Solaro 2003)
	47.7	41.44	(Walters et al. 2000)
Polypropylene (PP)	42.6	43.19	(Babrauskas 1992)
	46.5		(Tsiamis & Castaldi 2016, FAL 2011)
Polystyrene (PS)	41.6	40.19	(Lechner 2005)
	43.7		(Walters et al. 2000)
Polyvinyl chloride (PVC)	18.0	19.69	(Chielini & Solaro 2003, Tsiamis & Castaldi 2016, FAL 2011, TNO 2020)
	19.0		(Courtemanche & Levendis 1998, Shi 2015, Lechner 2005)
Polyethylene terephthalate (PET)	21.6	23.15	(Lechner 2005)
	24.2		(Walters et al. 2000)
Polyurethane (PU) foam	31.6	26.53	(RNS 2010)

*lower and higher limits, **average of the plastic's share in the world market

Considering the chemical structure of plastics (Figure 3), it should be noted that they are mainly composed of carbon and hydrogen (except for PVC), which, if burned, will not burden the atmosphere with toxic reaction products.

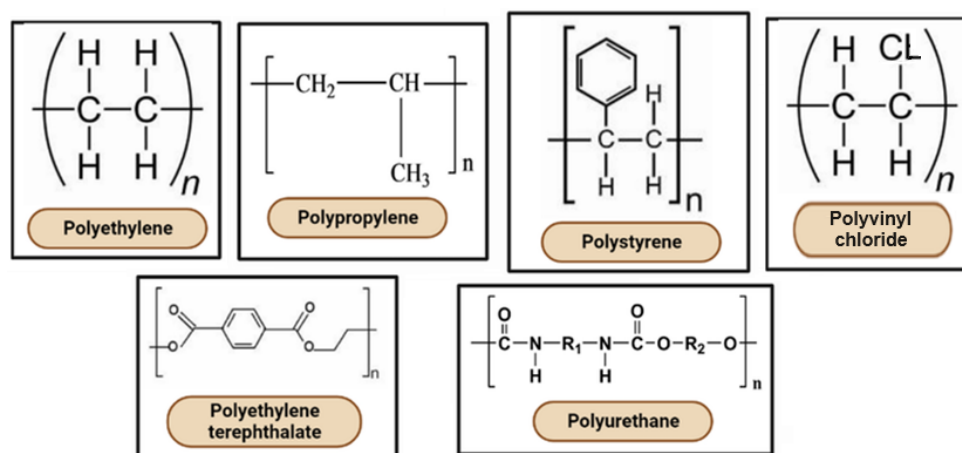


Fig. 3. Molecular structures of some of the commonly encountered polymers (Monkul & Özhan 2021, Sharma & Vuppu 2023)

Incineration of waste plastics is viable and can replace fossil fuels – similar chemical structure to fuel oil and comparable (to polyethylene, polypropylene or polystyrene) net calorific value of 42-46 MJ/kg. Currently, an acceptable process for treating plastic waste is incineration in cement kilns.

3.2. Recoverable energy from plastics

The net calorific value of plastics is a kind of determinant of the desirability of thermal disposal of waste from these materials. Before carrying out such a process, an important piece of information is a signal of how much energy can be recovered. Information on the proportion of energy used in the production of plastics is useful in this case, as the quotient of the net calorific value and the total energy consumption in the production of the product is the amount of energy that can be recovered (Marczak 2019).

In analyses of this type, when considering the total energy consumption for the production of a product, so-called raw material energy (energy obtained from crude oil – the raw material for the production of polymers) and process energy (energy used as fuel in processing – the production of plastics from monomers, i.e., e.g. polymerisation) are included.

Given the data (Table 2) on total energy consumption for plastic production, the amount of recoverable energy was calculated. Due to the different data (often inconsistent), certain assumptions were made in the calculations:

- the literature data are for Europe (Plastics Europe 2023, Karali et al. 2024),
- in the column "Energy consumption", the average value is rounded to the nearest whole number,
- in the column "Net calorific value", the average value is taken from Table 1 (according to literature data) and rounded up to a whole number.

Table 2. Energy recovery in relation to its consumption in the production of selected plastics

Polymer	Energy consumption MJ/kg	Calorific value LHV MJ/kg	Part of the recoverable energy	Reference
Polyethylene (PE)	80	46	0.6	(Thiriez & Gutowski 2006, Vlachopoulos 2009, Iwko & Wróblewski 2019, Plastics Europe 2023)
Polypropylene (PP)	78	45	0.6	(Gervet & Nordell 2007, Plastics Europe 2023)
Polystyrene (PS)	84	43	0.5	(Engelbeen 2022, Plastics Europe 2023, Karali et al. 2024)
Polyvinyl chloride (PVC)	59	19	0.3	(Thiriez & Gutowski 2006, Plastics Europe 2023)
Polyethylene terephthalate (PET)	71	23	0.3	(Plastics Europe 2023, Karali et al. 2024)
Polyurethane (PU)	94	32	0.3	(Plastics Europe 2023)

As the table shows, the highest data quotient (net calorific value and energy consumption) was obtained for PE and PP, with a value of 0.6. A high result was also obtained for PS, with a value of 0.5. Identical results were achieved for PVC, PET and PU, but with a slightly lower level.

It can be concluded that waste plastics will be an important source of energy that can be used in thermal technologies.

4. Concept for Harnessing the Energy Potential of Plastics

One of the thermal methods preferred for the disposal of waste plastics is incineration in cement kilns. Temperatures as high as 2073.15K (1800°C) in this process allow the plastics to burn completely – without the formation of harmful gases.

Much higher temperatures are reached during the detonation of the explosive, which can guarantee the complete and total combustion of such waste. During the explosive transformation of 1 kg of a BM, the temperature of the resulting gases reaches 4500K (4226.85°C) and energy from 2000-6000 kJ is released (Urbański 1954).

Commonly used blasting materials have lower detonation temperatures, on the order of 2500-3300K (2226.85-3026.85°C) for emulsion BMs (Silvestrov et al. 2014) and 2689-2861K (2415.85-2587.85°C) for ANFOs (Štimac et al. 2020), depending on charge diameter, pressure and detonation conditions. Their explosive decomposition results in reaching already high-temperature values, which is important for the thermal disposal of plastics.

Eliminating the wastes mentioned above by utilising their energy potential in explosive compositions would involve their use as additives in ANFO. Given the simple two-component explosive of this type (ammonium(V) nitrate and fuel oil), modification of its chemical composition is easy and reasonable.

Computer simulations carried out in the EXPLO5 programme (Sućeska 2001, Vasilescu et al. 2020) show the feasibility of designing different mixtures with the calculation of their thermodynamic parameters. Calculations are based on chemical formulae, heat of formation and density.

Although the method of plastic disposal by detonation is unconventional, preliminary studies and theoretical foundations (calculations of thermodynamic properties of modified mixtures) prove that it can be a promising form of plastic waste management (Biegańska & Barański 2017, 2018, Biegańska et al. 2018 a, 2018 b, Biegańska et al. 2022).

5. Conclusions

1. The unconventional method of disposal of plastics, which adds them as components of an explosive, results in disposal through a detonation process.
2. It is possible to replace the share of oil in ANFO with the addition of plastics and use the energy contained in them. The amount of energy that can be recovered is high for PE and PP (at 0.6) and PS – 0.5.
3. Implementing the explosive disposal method on an industrial scale (in mining) can be an alternative and cost-effective method for combustion processes.

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