ENERGY RECOVERY AS A SUSTAINABLE MEANS TO MANAGE POSTCONSUMER FOOTWEAR WASTE

Nakorn Tippayawong*[1], Korrakot Yaibuathet Tippayawong[2]

[1]Department of Mechanical Engineering, Faculty of Engineering, Chiang Mai University, Chiang Mai 50200 Thailand
[2]Department of Industrial Engineering, Faculty of Engineering, Chiang Mai University, Chiang Mai 50200 Thailand
**Correspondence, Tel.: +66-5394-4146, Fax: +66-5394-4145, E-mail: n.tippayawong@yahoo.com*

Introduction

All over the world, an increased generation of waste during production and at the end of use is a serious problem due to unsustainable consumption and economic growth. Waste management has become a major concern and one of the most important environmental and political issues in modern society. Importance of controlling and minimizing waste at source is recognized, but total waste elimination in the products' life cycle is impossible. Management of end-of-life waste is a major part of the integrated waste management concern.

In this work, the focus was on the footwear industry. The shoe industry has grown steadily over the past several decades, reaching almost 25 billion pairs of shoes a year (APICCAPS, 2015). While demand is rising, mass production lowers the price. Shoes often have a relatively short product life, resulted in a large waste stream. Even through significant efforts have been made to improve energy and material efficiency of the production process, not much has been placed in recovering and recycling of this post consumer footwear. Most of postconsumer shoes end up as waste, and are likely to be disposed of in landfills (Lee and Rahimifard, 2012).

In Thailand, managing end-of-life waste has still been a sole responsibility of governmental agencies and local authorities. Apart from recycling and recovery of material, one of the options advocated by waste management planners and government regulations is via energy recovery. Modern waste-to-energy (WTE) facilities with adequate and careful environmental monitoring have been shown to be a safe and cost effective technology. WTE conversion has a worldwide adoption and is becoming popular in Asia. It is also realized that WTE facilities may contribute to a positive cash flow in areas where tipping fees are high and landfill space is limited (Bebar et al., 2002).

Understanding and managing postconsumer footwear waste sustainably is of major concern. The present study gives a brief overview of end-of-life waste from the footwear industry and an integrated waste management with emphasis on energy recovery option. Challenges of waste management and energy recovery from used shoes are also outlined.

Waste from Footwear Supply Chain

Waste from shoe supply chain is generated throughout the chain (Fig. 1), starting at raw materials extraction, processing, component making, product assembly, sales and distribution, and at end-of-life. Waste generated are in various forms, solid, liquid and gas. Examples are raw material by-product, refuse, excess materials, disposed packaging materials, disposed end-of-use product, wastewater, chemicals, oils, and air pollutants.

Worldwide footwear consumption was increased from about 1 pairs of shoes per person per year in 1950 to 2.6 pairs per person per year in 2005. In 2010, worldwide production was about 20 billion pairs and expected to reach nearly 25 billion pairs in 2015. Dominant manufacturers are concentrated in Asia, accounting for almost 90% of the total global production output (APICCAPS, 2015). Footwear industry and leather products contributed to about 2% of Thailand gross domestic product. In 2010, Thailand was ranked 7th in terms of production volume at almost 250 million pairs. Domestic consumption was more than 160 million pairs a year (Laiwechpittaya and Udomkit, 2013). It was reported, on a global basis, that about 95% of shoes consumed annually are ended up in landfills (Lee and Rahimifard, 2012). It is expected that increased raw material costs, stakeholders' responsibility issue and more stringent environmental regulations will significantly affect the footwear industry.

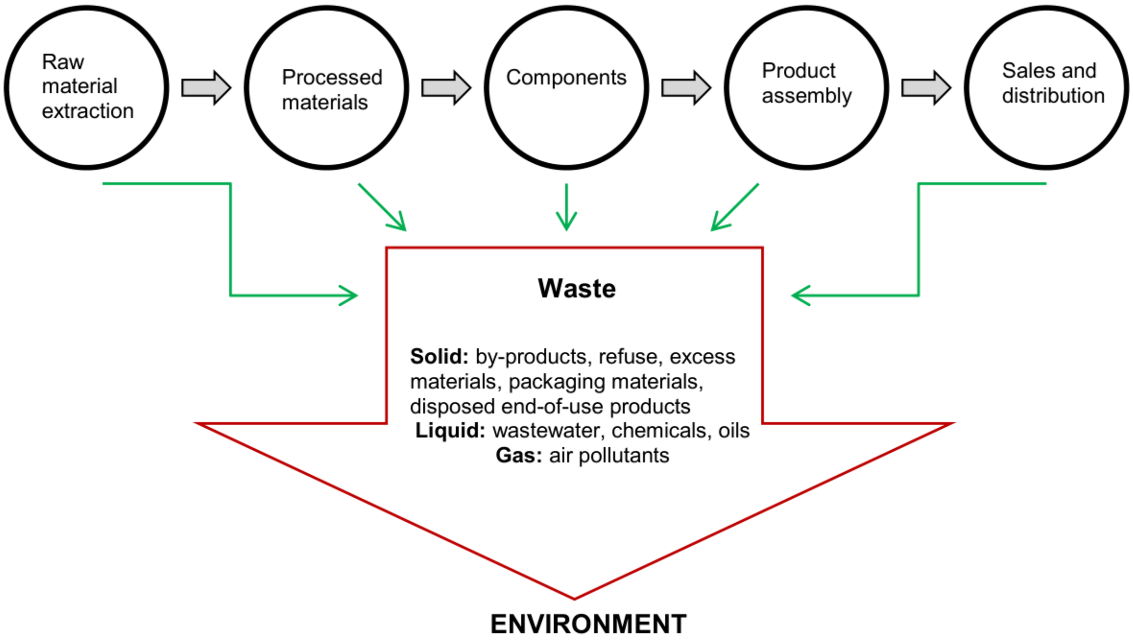

Figure 1. Waste generation from footwear supply chain

Typical Shoe Materials

In modern days, shoes are viewed as items of fashionable products that are not only used to protect and comfort, but also to enhance personal image. There are largely different types and styles of footwear, manufacturing from a wide variety of materials. Around 40 different natural and synthetic materials may be used to make shoes (Weib, 1999). Leather, rubber, plastics and textile are among the most common materials used. Table 1 shows the material composition of a typical footwear product. The diverse range of shoe types and complex mixture of materials pose serious challenges for recycling in an economically sustainable manner.

Component	(% w/w)
Leather	25
Rubber	23
Plastics	
Polyurethane	17

Ethylene vinyl acetate	14
Poly vinyl chloride	8
Textile and fabrics	6
Other (adhesives, metals, woods, etc.)	7

Table 1. Materials composition of a typical shoe (Weib, 1999)

Integrated Waste Management

The increase in waste generation has placed a tremendous pressure on the government and local authorities to manage it effectively. Thailand's present solid waste management strategy focuses on bulk collection and mass disposal. According to US Environmental Protection Agency (EPA), an integrated waste management is a comprehensive waste prevention, recycling and disposal program.

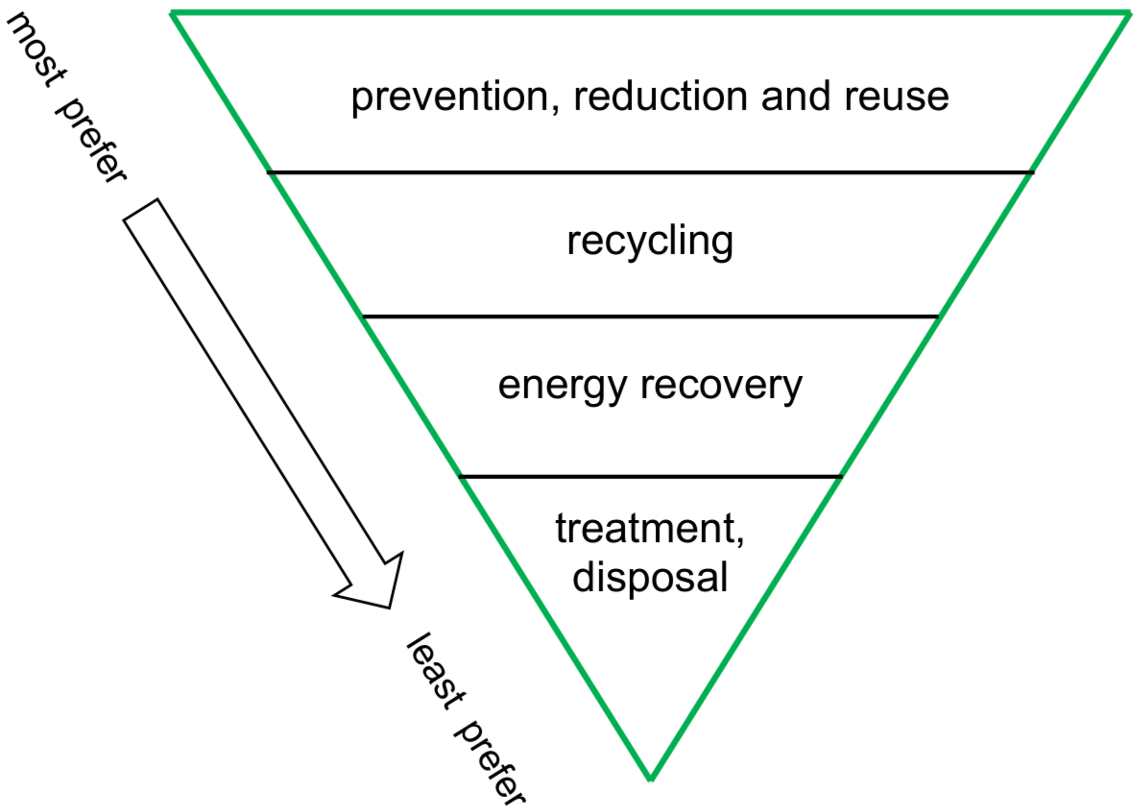

Figure 2. Integrated solid waste management hierarchy, based on EPA

4.1 Waste prevention

Waste prevention or source reduction seeks to avoid waste generation. Its strategies include using less packaging, designing products to last longer, and reusing products and materials.

4.2 Recycling

Recycling is a process involving collection, reprocessing, and recovering of valuable waste materials to make new materials or products.

4.3 Disposal

Usually, disposal includes treatment, incineration and landfilling. These activities are used to manage waste that cannot be recycled. Controlled burning of waste helps reduce its volume.

An effective waste management system considers prevention, recycling, and management of waste in such a way that most effectively protect human health and the environment. They range from the most to least preferable methods, Fig. 2. For footwear products, a waste management framework has been developed (Staikos and Rahimifard, 2007a). The proposed framework divides management options into proactive and reactive approaches. The major activities include waste prevention, minimization, reuse, recycling, energy recovery and, to a smaller extent, disposal in properly designed, constructed and managed landfills. Decision support tool and decision making model were developed in helping the footwear industry deal with its waste (Staikos and Rahimifard, 2007b; 2007c). Several cases were reported for material recycling, as well as studying value chain of used shoes (Lima et al., 2010; Lee and Rahimifard, 2012; Somboon and Tippayawong, 2015) A few studies were carried out for thermal conversion (Bahillo et al., 2004; Godinho et al., 2011).

5. Energy Recovery

Total waste elimination is impossible in the product life cycle. There will always be some fraction of waste that cannot be reused and recycled. They may be used to generate energy in terms of fuels, heat, or electricity. The chemical composition of shoe component is listed in Table 2. Using empirical formula shown in Eq. 1 (Demirbas, 1997) and average material composition, the average heating value of a typical shoe is estimated to be more than 20 MJ/kg, in similar range to coal.

$$HHV \text{ (MJ/kg)} = 33.5\,C + 142.3\,H - 15.4\,O - 24.5\,N \quad (1)$$

	C (%)	H (%)	O (%)	N (%)	S (%)	Cl (%)	water (%)	ash (%)
Leather	43.1	5.4	11.6	1.3	1.17	4.97	10.0	22.5
Plastic	56.4	7.8	8.1	0.9	0.29	3.00	15.0	8.6
Textile	37.2	5.0	27.1	3.1	0.28	0.27	25.0	2.0
Wood	41.2	5.0	34.5	0.02	0.07	0.09	16.0	2.8

Table 2. Composition of common materials used for footwear

where *HHV* is the higher heating value of fuel. *C*, *H*, *O* and *N* are carbon, hydrogen, oxygen and nitrogen contents (% by weight of fuel), respectively.

It was clear that energetic content of a shoe was quite high. They may be used as fuels via WTE conversion which includes several established and emerging technologies such as refuse derived fuel (RDF) production, and thermochemical conversion technologies including combustion, gasification and pyrolysis.

5.1 Physical upgrade

The postconsumer shoe waste as solid fuel is composed of combustible components (plastics, rubber and leather, textiles and woody matter). The proportion varies, depending on designs and recycling programs. The RDF production may be accomplished through successive treatment stages of screening, shredding, size reduction, classification, separation, drying, densification, and storage. The processed solid fuel has a number of advantages over untreated waste which are the higher calorific value, the homogeneity of physico-chemical composition, the ease of storage, handling and transportation. RDF technology and equipments are well established for handling municipal solid waste. However, no system has yet been designed for shoe waste. Modifications of existing hardware as well as new development may be required specifically for it.

5.2 Thermochemical conversion

Direct combustion or incineration is the most common WTE approach. More advanced thermochemical conversions such as gasification and pyrolysis have been established. Each technology gives a different range of products, sets different requirements for the input, and operates in different modes (Table 3).

	Combustion	Gasification	Pyrolysis
Temperature (°C)	800–1450	500–1800	250–900
Pressure (bar)	1	1–45	1
Atmosphere	Air	Air, O_2, H_2O	Inert
Stoichiometric ratio	≥ 1	<1	0
Products:			
Gas phase	CO_2, H_2O, O_2, N_2	H_2, CO, CO_2, CH_4, H_2O, N_2	H_2, CO, H_2O, N_2, hydrocarbons
Solid phase	ash, slag	slag, ash	char
Liquid phase			bio-oil, water

Table 3. Characteristics of main thermal technologies considered (Bosmans et al., 2013).

Combustion

Combustion is basically a rapid, high temperature oxidation of the combustible components contained in the waste. It is used to treat a wide range of wastes. The main mechanisms are drying and degassing, devolatilization, and oxidation. During combustion, flue gases (CO_2, H_2O, O_2, N_2) are generated that contain the majority of the available fuel energy as heat. Tiny amounts of CO, NO_X, SO_2, volatile organic and heavy metal compounds may be formed. Nevertheless, burning of waste can be an environmentally friendly method if combined with energy recovery, emissions control and an appropriate disposal method for the remains. The following types of combustor are most frequently encountered in practice: grate incinerators, rotary kilns and fluidized beds, with heat exchangers to generate high pressure steam. The steam is piped directly to drive turbo-generators. Air pollution control devices such as dry, semi-dry and wet scrubbers to remove acid gas, heavy metals, dioxin and furans, bag filters and electrostatic precipitator to remove large and small particulate matter as well as dust are usually employed.

Gasification

Gasification is thermal decomposition and reformulation of organic materials at elevated temperature (500–1800 °C) to produce a fuel gas. The fuel gas contains CO, H_2, CH_4, CO_2, H_2O, N_2, trace amounts of higher hydrocarbons and various contaminants such as tar and char particles. This gas can be used as a fuel for efficient production of heat and/or electricity, or as a feedstock for synthesis of chemicals. A gasification reactor or gasifier can use air, oxygen, steam, carbon dioxide or a mixture of these as gasification agents. The three main gasifier types are fixed bed, fluidized bed, and entrained flow gasifiers. Example of a gasification process is schematically shown in Fig. 3.

Pyrolysis

Pyrolysis is thermal degradation of organic materials in the absence of an oxidizing agent, or with only a limited supply at relatively low temperatures (400–900 °C) to produce pyrolysis gas, liquid and solid char. Proportions of the three products depend on the pyrolysis method and process parameters. Conventional pyrolysis reactors include fixed bed, fluidized bed, entrained flow, moving bed, rotary kiln, and ablative reactor. Example of a pyrolysis process is schematically shown in Fig. 4.

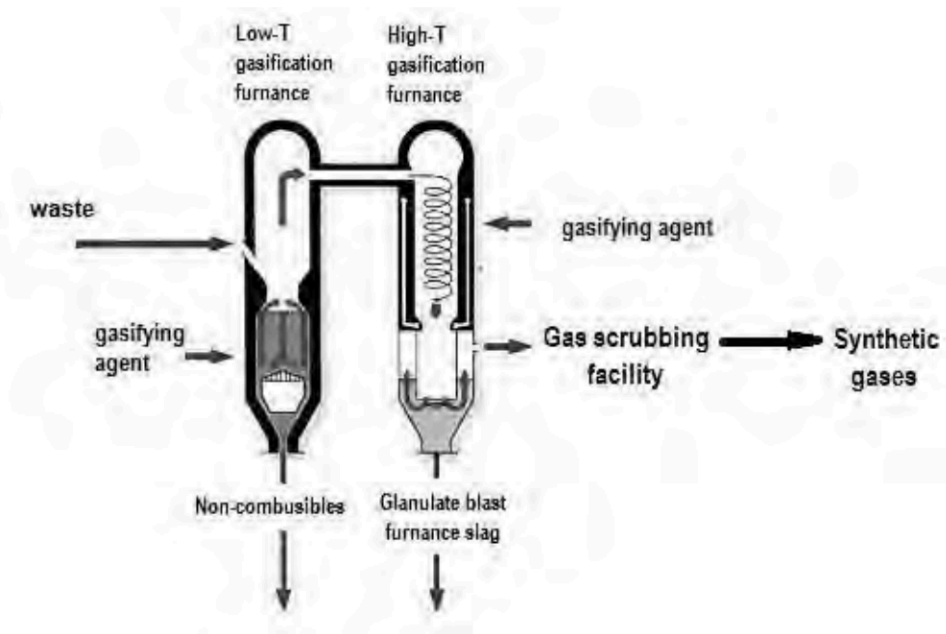

Figure 3. Gasification process for converting waste to fuel gas

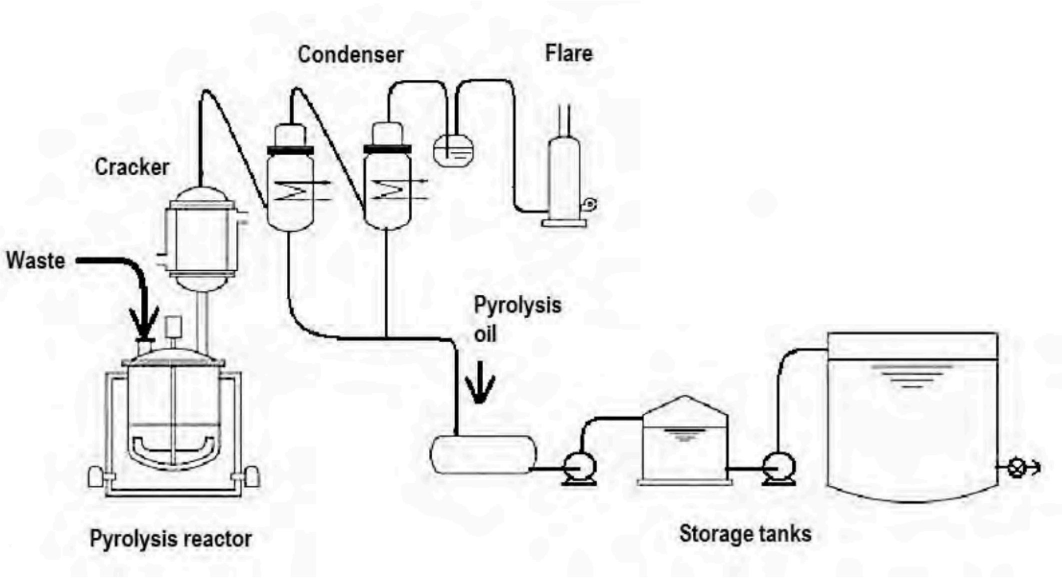

Figure 4. Pyrolysis process for converting waste to bio-oil

6. Challenges in Management of Postconsumer Footwear Waste

Increased raw material costs, public concern, manufacturers' responsibility issue and tighter environmental legislations are expected to challenge the way the footwear industry, the relevant governmental agencies, as well as the customers currently deal with the postconsumer waste.

Rethink - The shift in thinking for customers, manufacturers and governmental agencies is required to manage the waste sustainably. This involves changes in values and behaviors, which will switch to adopt better systems of manufacturing, distributing, using, servicing, and regulating the industry.

Reuse and Recycle – Structural changes to the footwear industry may be required throughout the supply chain from production to end-of-life to accommodate successful recycling program. Sustainable reverse logistics in the sector as well as value recovery chain may be established. New generation of recycling processes should be developed.

Recovery of energy – Landfilling must be the last method adopted. Those wastes that are not ultimately recycled must be treated possibly by energy recovery option. However, waste treatment infrastructure is almost non-existent. National strategies or incentives for development of new technologies are not clear and still lacking. Demonstration of the technology may be needed.

7. Concluding Remark

Tremendous amount of used shoes waste is generated every year. Sustainable management of footwear waste is needed. In this study, a brief overview of postconsumer footwear waste was presented. Energy recovery options to deal with ultimate non-recyclable waste were highlighted. Apart from waste prevention and recycling, the end-of-life WTE recovery can be not only environmentally friendly, but may also be economically justified.

Acknowledgement

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