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Problems and resolutions in dealing with waste disposable paper cups

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ABSTRACT

In recent years, the problem caused by waste disposable paper cups (WDPCs) has became a topic of great concern to scientists, and commercial companies have also begun to take an interest in developing processes for tackling the issue. In this review, the inherent problems and social barriers during the recycling of WDPCs are described. This review presents the major conclusions of previously published works focused on the utilisation of WDPCs for material and energy purposes. The commercial utilisation of WDPCs is also described. Some suggestions for better recycling of WDPCs are given in the final part of this work.

Keywords: *waste disposable paper cups, polypropylene composite, grapheme, pyrolysis, vermicomposting, commercial utilisation*

1. Introduction

Disposable paper cups used for serving coffee, tea and other drinks contain high quality virgin cellulose fibre board (95 wt%) combined with a thin internal polyethylene (PE) coating (5 wt%)[1,2]. They are typically employed where washing and sanitising of reusable cups is awkward, such as in hospitals, in the entertainment and transportation sectors, and for occasional use by large numbers of people in short time intervals which makes reusable cup service practically impossible.

Disposable paper cups were introduced for replacing the unhealthy common drinking cups near public drinking water facilities. However, in the second half of the previous century, a problem has arisen as a result of a superfluous generation of waste disposable paper cups (WDPCs) (Figure 1)[3]. Considering only the USA, more than 50 billion disposable paper cups are thrown away each year[4]. In mainland P.R. China, approximately 10 billion disposable paper cups are sold annually[5]. An estimated 2.5 billion disposable paper cups are used in the UK each year[6]. Australia's obsession with coffee has led to an extra 7,000 tonnes of non-recyclable waste from

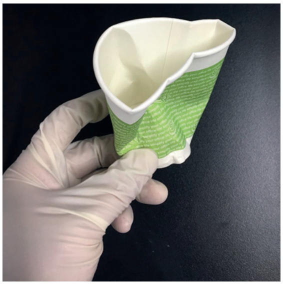

Figure 1 *A waste disposable paper cup. Modified from ref.*[21].

disposable paper cups[7]. In Taiwan, the chain beverage stores, convenience stores and fast food stores use around 1.5 billion disposable paper cups per year[8].

The vast majority of WDPCs are disposed of to landfill or *via* combustion instead of being recycled[1]. However, these two processes are regarded as environmentally unfriendly because of the generation of toxic gases and contaminative leachate[9]. The most innovation on WDPCs disposal has come in the field of composting, and that is still limited at best[10]. Effective utilisation of WDPCs could not only reduce the amount of municipal solid waste (MSW), but also contribute towards environmental conservation. Therefore, there is an urgent need for a better understanding of WDPCs. This review aims to point out the problems in dealing with WDPCs, and provide updated technical information on the utilisation of WDPCs.

2. Problems

2.1 Inherent problems

The main problem is the mass misconception that WDPCs, because they are usually made of paper, are recyclable in the same manner as any other forms of packaging waste. The truth of the matter is that WDPCs cannot be easily recycled. The glue that holds the parts of the cup together and contamination in the cups cannot be removed in the recycling process. So far, the greatest problem has been the strong adhesion between the paper board and the thin coating of PE[1,6]. The coating poses a mammoth problem for the recycling industry, because it cannot be separated out in a standard recycling mill[11,12]. Even the smallest amounts of plastics can wreak havoc with paper reclamation equipment and contaminate downstream processes[13]. In fact, almost all recycling plants reject WDPCs and send them straight to landfill. The decomposition process in the landfill releases methane, a greenhouse gas which is estimated to possess 23 times the heat-trapping power of carbon dioxide[14]. In the USA, it is estimated that fewer than one in 400 WDPCs get sent for recycling, and the rest end up in landfill sites for decades, taking about 20 years for a cup to decompose[15].

2.2 Social barriers

The successful recycling of WDPCs is dependent upon multiple factors, including local government policies and access to recycling sites such as paper mills and plastic processors. The reality is the recycling of WDPCs is only possible in highly specialised recycling facilities, however there is currently a limited number of recycling facilities that can process PE-infused paper cups[11]. For WDPC recycling to become a reality, they need to be collected systematically in bulk. Since consumers often take their beverages with them when they leave the coffee bar or fast food chain, WDPCs end up everywhere with the exception of proper collection systems[13]. Therefore, a mass collaboration between municipalities, landlords, manufacturers, vendors, customers and even adjacent businesses is necessary for the recycling of WDPCs.

3. Resolutions

3.1 Laboratory study

3.1.1 Conversion of WDPCs into useful materials

It has been reported by Mitchell *et al.* that WDPCs have potential to be reused as reinforcement in novel polypropylene (PP) composites[1]. In their work, WDPCs were firstly shredded to form paper plastic laminates (PPL) flakes. The PPL flakes and PP were mixed, extruded, pelletised and injection moulded at 160 to 180 °C. Use of a maleated polyolefin coupling agent allowed composites containing 40 wt% of PPL flakes to increase the tensile strength of PP by 50% to 30 MPa. The Young's modulus also increased from 1 to 2.5 GPa and the work to fracture increased by a factor of 5.

Graphene is a rapidly rising star on the horizon of materials science and condensed matter physics. Generally, there are two fundamental sources for the preparation of graphene: graphite and organic molecules. Zhao *et al.* made a novel endeavour by using WDPCs as a carbon source and Fe^{2+} as a catalyst to form graphene sheets with Fe particles deposited onto them. The Fe/graphene composite can be used as an anode material for lithium ion batteries, or be converted to high-quality graphene sheets in high yield when Fe particles were completely removed[16].

3.1.2 Pyrolysis of WDPCs

Pyrolysis is the thermal degradation of organic substances under an inert atmosphere into valuable products such as oil, solid residue and gaseous phases, and it is considered efficient and environmentally-friendly because no waste is produced[17]. There are two types of pyrolysis: analytical and applied. Applied pyrolysis is carried out for the purpose of producing chemicals. Analytical pyrolysis involves the characterisation of the analyte by decomposition upon heat treatment in the absence of oxygen[18]. This technique enables us to understand the decomposition pathway of the analyte. Applied pyrolysis of paper cup waste was performed by Biswal *et al.* in a semi-batch reactor with a temperature range of 325 to 425 °C and at a heating rate of 20 °C min^{-1} (see ref.[2]). The maximum oil yield was 52% at a temperature of 400 °C. The functional groups present in the oil are aldehydes, ketones, carboxylic acids, esters, alkenes, and alkanes. It was also found that the pyrolytic oil contains around 18 types of compounds having a carbon chain length in the range of C_6–C_{20}. Thermogravimetric analyser (TG) plays an important role in the field of analytical pyrolysis, which can reveal the change of mass loss with temperature. Pyrolysis of WDPCs was investigated by Jankovic[19] using the TG technique, then a kinetic study was performed based on the original TG data. The active pyrolytic zone was indentified in a temperature range of 250 to 400 °C, indicating the pyrolysis of cellulose, and the average activation energy of the pyrolysis reactions was calculated to be 135.8 kJ mol^{-1}. Information about the evolved species is even more important for understanding the pyrolysis process. TG coupled with Fourier transform infrared spectroscopy (TG-FTIR) is a valuable technique for obtaining mass loss with time and probing the functional groups of volatile species evolved from pyrolysis on-line[20]. It was found by Song *et al.* that the gaseous products of WDPC pyrolysis were mainly emitted at about 360 °C. Ketones were the most abundant condensable organic products, followed by ethers, alcohols and aromatics. CO_2 was the dominating gaseous product, followed by CO. These gases can also be produced *via* secondary cracking of the small molecule organics above 400 °C. The cracking of PE led to the formation of a large amount of hydrocarbons around 485 °C (see ref.[21]). Figure 2 shows the evolution histories of the evolved species mentioned above as a function of temperature.

3.1.3 Vermicomposting technology

Earthworms play an important role in the monitoring of environmental pollution. Vermicomposting technology was found to be an effective method for the conversion of WDPCs into nutrient-rich manure and at the same time earthworms were involved in the process to separate the plastic coating from the paper. Karthika *et al.* reported that WDPCs can be provided as feed for earthworms, and a high degree of organic matter stabilisation was achieved when WDPCs were subjected to the vermicomposting process in a 1:1 ratio along with cow dung. Changes in the normal

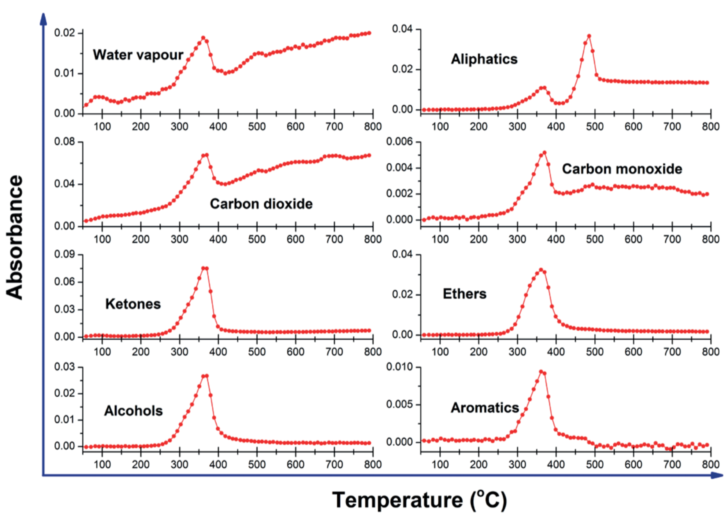

Figure 2 *Evolution histories of the evolved species during pyrolysis of WDPCs. Modified from ref.*[21].

Figure 3 *WDPCs can be used to produce WDPC-derived high quality papers. Credit: James Cropper PLC.*

metabolism of the earthworm and tissue damage in the earthworm can be observed during the vermicomposting process. However, earthworms had the capacity to regain their body mass when inoculated into a new environment[14,22].

3.2 Commercial approach

The British master papermaker James Cropper announced in July 2013 that it had created a method to recycle WDPCs into high quality paper products. WDPCs and WDPC-derived paper products are shown in Figure 3. The process involves softening WDPCs in a warmed solution, which separates the plastic coating from the fibre, then the plastic is skimmed off, leaving water and pulp after which impurities are filtered out, leaving a high-grade pulp[23,24]. In 2013, the company opened a reclaimed fibre plant using this technology at its production mill in Kendal, Cumbria, UK[25]. The company has built a recycling partnership with McDonald's since 2016. Non-recyclable paper cups used in McDonald's restaurants across the UK are saved from landfill and incineration, the paper contained in WDPCs can thus be converted back into FSC® – certified fibre for the production of luxury papers and packaging materials, and the remaining plastic is suitable for use in garden furniture[26].

4. Conclusions

Although the paper fibre is recyclable, the plastic coating can greatly limit the recyclability of WDPCs. Proper collection systems are needed for the successful recycling of WDPCs. Laboratory studies showed that WDPCs can be used as raw materials for the production of high strength plastics and graphene. Hydrocarbon liquid can be produced from WDPCs *via* pyrolysis. Pyrolysis characteristics and kinetics of WDPCs have also been studied by TG-FTIR. Vermicomposting technology was also found to be an effective method for the degradation of WDPCs. The recycling technology created by the James Cropper Company in the UK can separate out the plastic incorporated into WDPCs, leaving paper pulp, which can be used in the industrialised production of high quality papers.

5. Suggestions

(1) The real key to change is education. The public needs to recognise that WDPCs cannot be easily recycled in the same manner as conventional paper waste.

(2) To recycle WDPCs more efficiently, co-operation between large companies is of great importance. Also, municipal departments should establish targeted systems for the collection of WDPCs.

(3) Energy utilisation of WDPCs *via* thermal conversion is suggested because it avoids the problems caused by separating the thin PE-coating from paper.

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7. References

1. Mitchell, J., Vandeperre, L., Dvorak, R., *et al*. (2014) *Waste Manag*., **34**, 2113–2119.
2. Biswal, B., Kumar, S. and Singh, R.K. (2013) *J. Waste Manag*., **2013**, 1–7.
3. Potting, J. and van der Harst, E. (2015) *Int. J. Life Cycle Ass*., **20**, 1143–1154.
4. One Green Planet (n.d.) Your coffee habit may be harming the environment – here's what you can do now. http://www.onegreenplanet.org/environment/paper-cup-waste-and-environment/ [accessed 1 November 2017].
5. Ni, H. (2011) China's annual sales of 10 billion cups rarely recycled. http://finance.ifeng.com/news/macro/20111026/4928468.shtml [accessed 1 November 2017].
6. Smithers, R. (2017) *The Guardian*. 30 March. https://www.theguardian.com/environment/2017/mar/30/reusable-incentives-could-slash-disposable-coffee-cup-waste [accessed 1 November 2017].
7. ONYA Life (n.d.) Disposable coffee cups; the true cost of your takeaway coffee. https://www.onyalife.com/zero-waste/disposable-vs-reusable-coffee-cups/ [accessed 1 November 2017].
8. Houng, H., Shen, S.-H. and Ma, H.-K. (2014) Municipal solid waste management in Taiwan: From solid waste to sustainable material management. In: Pariatamby A. and Tanaka, M. (eds), *Municipal solid waste management in Asia and the Pacific Islands. Environmental science and engineering*, pp. 317–336. Springer, Singapore.
9. Hong, J., Chen, Y., Wang, M., *et al.* (2017) *Renew. Sust. Energy Rev*., **69**, 168–176.
10. Earth 911 (n.d.) How to recycle paper cups. http://earth911.com/recycling-guide/how-to-recycle-paper-cups/ [accessed 1 November 2017].
11. BBC News (2016) Viewpoint: The waste mountain of coffee cups. http://www.bbc.com/news/magazine-36882799 [accessed 1 November 2017].
12. Gardner, E. (2017) Pointless waste: the problem with disposable coffee cups. https://www.packaging-gateway.com/features/featurepointless-waste-the-problem-with-disposable-coffee-cups-5845883/ [accessed 1 November 2017].

13. Recyclingbin.com (2010) Disposable cups – recycling one drink at a time. http://www.recyclingbin.com/Blog/disposable-cups-recycling-one-drink-at-a-time [accessed 1 November 2017].
14. Karthika, A., Seenivasagan, R., Kasimani, R., *et al.* (2017) The role of *Eudrillus eugenia* in the degradation of paper cup waste and the morphological, physiological and histological changes in the organism. In: Prashanthi M., Sundaram R., Jeyaseelan A. and Kaliannan T. (eds), *Bioremediation and sustainable technologies for cleaner environment. Environmental science and engineering*. pp. 65–76. Springer, Cham.
15. Greener Idea (2016) What can be done to reduce disposable coffee cup waste? https://greenerideal.com/infographics/what-can-be-done-to-reduce-disposable-coffee-cup-waste-infographic/ [accessed 1 November 2017].
16. Zhao, H. and Zhao, T.S. (2013) *J. Mater. Chem. A*, **1**, 183–187.
17. Chen, D., Yin, L., Wang, H. and He, P. (2014) *Waste Manag.*, **34**, 2466–2486.
18. Akalın, M.K. and Karagöz, S. (2014) *TRAC-Trends Anal. Chem.*, **61**, 11–16.
19. Janković, B. (2014) *Energ. Convers. Manage.*, **85**, 33–49.
20. Chen, D., Liu, D., Zhang, H., *et al.* (2015) *Fuel*, **148**, 79–86.
21. Song, D., Wang, J., Zhang, Y. and Ma, Y. (2017) *Prog. React. Kinet. Mec.*, **42**, 126–135.
22. Arumugam, K., Ganesan, S., Muthunarayanan, V., *et al.* (2015) *Environ. Sci. Pollut. Res.*, **22**, 2868–2876.
23. Moore, D. (2013) "World's first" disposable cup recycling plant set to open in UK. http://ciwm-journal.co.uk/worlds-first-disposable-cup-recycling-plant-set-to-open-in-uk/ [accessed 1 November 2017].
24. Paperless Kitchen (n.d.) New solution for paper cup waste recycling. https://www.paperlesskitchen.com/blogs/news/8384129-new-solution-for-paper-cup-waste-recycling [accessed 1 November 2017].
25. Elks, J. (2013) UK Paper company might just rid the world of paper cup waste. http://www.sustainablebrands.com/news_and_views/waste_not/uk-paper-company-might-just-rid-world-paper-cup-waste [accessed 1 November 2017].
26. Moore, D. (2016) McDonald's UK to trial plastic-coated paper cup recycling. http://ciwm-journal.co.uk/mcdonalds-uk-to-trial-plastic-coated-paper-cup-recycling/ [accessed 1 November 2017].