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A review on automated sorting of source-separated municipal solid waste for recycling

Sathish Paulraj Gundupalli [a], Subrata Hait [b], Atul Thakur [a,*]

[a] Department of Mechanical Engineering, Indian Institute of Technology Patna, Bihta, Patna, Bihar 801103, India
[b] Department of Civil and Environmental Engineering, Indian Institute of Technology Patna, Bihta, Patna, Bihar 801103, India

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ABSTRACT

A crucial prerequisite for recycling forming an integral part of municipal solid waste (MSW) management is sorting of useful materials from source-separated MSW. Researchers have been exploring automated sorting techniques to improve the overall efficiency of recycling process. This paper reviews recent advances in physical processes, sensors, and actuators used as well as control and autonomy related issues in the area of automated sorting and recycling of source-separated MSW. We believe that this paper will provide a comprehensive overview of the state of the art and will help future system designers in the area. In this paper, we also present research challenges in the field of automated waste sorting and recycling.

Contents

Abbreviations: ABS, acrylonitrile butadiene styrene; ACQ, alkaline copper quat; ADC, analog digital converter; Al, aluminum; As, arsenic; Au, aurum (gold); CCA, chromate copper arsenate; CCD, charge coupled devices; CBR, case-based reasoning; C&D, construction and demolition; C/H, carbon and hydrogen; CMOS, complementary metal oxide semiconductor; Cr, chromium; Cu, copper; DAQ, data acquisition; DE-XRT, dual energy X-ray transmission; DNA, deoxyribonucleic acid; EDXRF, energy dispersive X-ray fluorescence; EMS, electromagnetic sensor; FUSSER, fuzzy spectral and spatial classifier; GDP, gross domestic product; HDPE, high-density polyethylene; HIPS, high impact polystyrene; HIS, hue saturation and intensity; HSI, hyperspectral imaging; ICA, independent component analysis; KNN, k-nearest neighbor; LDPE, low-density polyethylene; LED, light-emitting diode; LIBS, laser induced breakdown spectroscopy; LIPS, laser induced plasma spectroscopy; MDS, magnetic density separation; Mg, magnesium; MIR, midrange infrared; MSW, municipal solid waste; Nd:YAG, neodymium-doped yttrium aluminum garnet; NdFeB, neodymium magnets; NF, non-ferrous; Ni, nickel; NIR, near infrared; OCC, old corrugated cardboard; ONP, old news paper; Pb, lead; PC, polycarbonate; PCA, principal component analysis; PE, polyethylene; PET, poly(ethylene terephthalate); PLA, polylactide; PPP, purchasing power parity; PP, polypropylene; PS, polystyrene; PSW, plastic solid waste; PVC, poly(vinyl chloride); PU, processing unit; SS, stainless steel; SVS, smart vision system; RGB, red green blue; Rx, receiver; Tx, transmitter; UNEP, united nations environment programme; UV, ultraviolet; VIS, visual image spectroscopy; WP, white paper; XRF, X-ray fluorescence; XRT, X-ray transmission; Zn, zinc; 3D, three-dimensional.

* Corresponding author.
E-mail addresses: sathish.pme14@iitp.ac.in (S.P. Gundupalli), shait@iitp.ac.in (S. Hait), athakur@iitp.ac.in (A. Thakur).

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1. Introduction

Rapid urbanization and industrialization is causing an unprecedented rise in the generation of municipal solid waste (MSW) worldwide (Chiemchaisri et al., 2007; Liu and Wu, 2010; Saeed et al., 2009). Countries with a relatively higher GDP tend to produce a larger quantity of MSW (see Fig. 1(a)). Projections show that the generation of MSW across major metropolitan cities worldwide will rise from 1.3 billion tonnes in 2012 to 2.2 billion tonnes in 2025 (Hoornweg and Bhada-Tata, 2012; Kawai and Tasaki, 2016). MSW is often a rich source of various useful recyclable materials such as metal, paper, plastic, and glass (see Fig. 1(b)). Effective MSW management can enable recovery of valuable recyclable materials and reduction of negative environmental impact. Waste sorting is a key step in MSW management for the recycling of materials. Researchers worldwide have been actively exploring automated sorting techniques for efficiently processing increasing quantities of MSW. This paper summarizes developments that have taken place in the last decade in the area of automated sorting and recycling of source-separated MSW.

At the waste collection stage, source segregation is often performed for a preliminary sorting of recyclables. The practice of source segregation may not be followed uniformly at all the locations and the extent of required sorting may vary. Developing countries seldom practice source segregation. In this review, we assume that the practice of source segregation is performed and thus the input to the automated waste sorting process is source-separated MSW.

Following some early patents filed by Holloway (1989) and Roman (1992), many other automated solid waste sorting techniques have been reported by archival journals and technical conferences. Several review articles have been reported frequently in areas related to automated/semi-automated waste sorting for recycling and are as follows:

- Dodbiba and Fujita (2004) surveyed various sorting techniques for separating plastic materials. The review primarily focused on non-sensor based design, development, and testing of wet and dry based separating/sorting techniques.
- Shapiro and Galperin (2005) reviewed various air classification techniques for solid particles.
- Al-Salem et al. (2009) reviewed chemical recycling and energy recovery from plastic solid waste (PSW).
- Sadat-Shojai and Bakhshandeh (2011) reviewed energy recovery, mechanical and chemical recycling and separation methods by recycling Poly(vinyl chloride) (PVC) waste.
- Gaustad et al. (2012) surveyed physical and chemical separation methods in sorting and removal of impurities from aluminum debris.
- Wu et al. (2013) reviewed triboelectrostatic separation techniques for sorting plastic from waste.
- Rahman et al. (2014) reviewed sorting techniques to segregate waste paper and also recommended low cost sorting techniques corresponding to the paper type present in the waste.
- Cimpan et al. (2015) reviewed physical processing of waste to segregate recyclables from MSW. The review mainly focused on case studies of operational experience without emphasizing many aspects of automation including material handling, sensors and control.
- Wang et al. (2015) published a comprehensive review on flotation separation of various types of plastics from waste.

This paper provides a comprehensive overview of the state of the art in the field of automated sorting of source-separated MSW for the purpose of recycling. This paper is intended to help designers of automated waste sorting systems select suitable technologies such as sensors, actuators, control algorithms, and sorting processes for recycling source-separated MSW. This review presents a detailed discussion on various comminution and sorting techniques used for segregating recyclable materials. The paper also presents a detailed discussion on the variety of materials that can be sorted as well as the sensors and material handling systems used. In addition, classification rates obtained by various sorting techniques reported in the literature in the last decade are detailed. A detailed discussion on the levels of automation implemented in the waste sorting systems is presented. This review also identifies open research issues and suggests future research directions in the field of automated waste sorting.

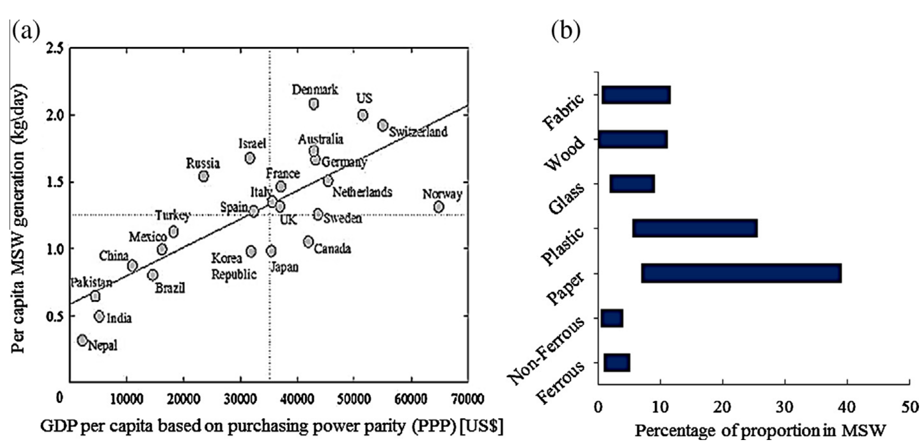

Fig. 1. (a) Per capita MSW generation versus GDP per capita based on purchasing power parity. (b) Proportion of recyclables in MSW. *Source:* ADB (2013), Annepu (2012), Badgie et al. (2012), Banar et al. (2009), Burnley (2007), Damanhuri et al. (2014), Edjabou et al. (2015), EOCSSB (2012), EPA (2014), Hoornweg and Bhada-Tata (2012), Khatib (2011), Masood et al. (2014), MfE (2009), Montejo et al. (2011), OECD (2012), Randell et al. (2014), Sharma and McBean (2007), and UNEP (2012).

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