Environmental Assessment of Recyclable Waste Valorization in United Arab Emirates

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Abstract. The United Arab Emirates (UAE) has one of the largest per capita carbon footprints and solid waste generation rates in the world. In preparation for the post-oil future, the UAE has planned to diversify its energy mix with renewable sources. Waste valorization, particularly material and energy recovery (MER), presents a promising solution for the waste and energy challenges of the future. It is thus of great importance to ensure that the shift to MER systems lead to a concomitant positive impact on the environment. This research aims to assess the environmental impacts of selected waste management strategies incorporating MER systems in the UAE. The study is focused on the valorization of recyclable wastes through incinerators and/or material recovery facilities (MRFs) compared to existing landfill practices. The mass burn strategy increased the energy produced by 88% compared to the combined MER strategy due to the high energy yield of recyclables. It was found that combining energy and material recovery was the optimum environmental option in terms of global warming and abiotic depletion. The mass burn strategy had a favourable positive impact on freshwater aquatic ecotoxicity and human toxicity, yet it resulted in the highest acidification potential (ACP) and eutrophication potential (ETP). On the other hand, the MRF strategy achieved positive ACP and ETP impacts. Overall, all MER-based strategies achieved better environmental performance compared to existing landfilling practices.

1. Introduction

Newly industrialized countries like the United Arab Emirates (UAE) are confronted with numerous waste management problems due to the significant increase in municipal solid waste (MSW) generation in the last few decades. This is largely because of rapid population growth, economic development, and high-consuming society. With a current population of 9.6 million, the waste generation rate was reported to be 1.76 kg/capita/day, which translates to an annual total waste generation of ~6.2 million Mg, most of which is disposed of in landfills [1]. Based on the annual population growth rate of 2.67%, waste generation is estimated to reach ~18 million Mg per year by 2040. Recyclables account for 51% of the total average composition of MSW generated in UAE [2], distributed as 25% paper, 19% plastic, 4% glass, and 3% metal [3]. In response to the challenges associated with traditional waste management methods, the shift to material and energy recovery (MER) systems has become more attractive.
Assessing the environmental effects of waste valorization strategies is vital to strategically prioritize projects and to achieve sustainability [4]. One of the methods to study the environmental impacts is the life cycle assessment (LCA), which is a holistic methodology that considers all environmental burdens throughout the life cycle of products and processes, from cradle to grave [5]. The LCA is suitable for application in waste management due to the complexity of the systems, multiple processes involved, and numerous varying parameters [6].

Recent LCA studies agree that MER systems are more environmentally favorable than landfills over their life cycle. Nevertheless, the performance of such technologies varies depending on specific local conditions, assessment boundaries, input data, and assumptions. For instance, in contradiction to Burnley et al. [7], Buttol et al. [8] and Tunesi [9] found that incineration had a positive environmental impact on acidification and eutrophication compared to landfilling. Likewise, Liamsanguan and Gheewala [10] depicted that incineration was more environmentally superior to landfilling in terms of greenhouse gas (GHG) emissions. Demetrious and Crossin [11] found that treating paper waste in incineration or gasification-pyrolysis produces less GHG emissions than in landfill, while plastic was best managed in landfill. On the other hand, Wang et al. [12] stated that when the total steel and plastic waste were recycled, maximum energy conservation and carbon dioxide (CO₂) reduction were achieved.

Overall, the reviewed literature contains limited research on the environmental performance of MER facilities, locally and regionally. The main purpose of this study was to assess the different environmental impacts of selected waste management strategies incorporating MER systems using an LCA approach. The study was focused on the management of recyclable waste materials through incinerators and/or material recovery facilities (MRFs). The relative performance of the examined individual and combined MER systems was assessed in terms of multiple environmental impacts categories.

2. Methodology

The International Organization for Standardization (ISO) provides a set of guidelines (14040-14044) for LCA studies [12]. The standard stages of an LCA study comprise: 1) goal and scope definition, 2) life cycle inventory (LCI), 3) life cycle impact assessment (LCIA), and 4) interpretation, as discussed in the following sections.

2.1. Goal and Scope Definition

The main goal of this study was to evaluate the environmental burdens associated with the management of recyclable materials under specific valorization strategies compared to existing practices. The assessed waste management strategies in this study are based on incineration and MRFs compared to the existing landfill practices. The functional unit to which all inputs and outputs of the study are referred to be the management of 1 Mg of recyclable waste. The proposed LCA system boundary includes the separation, treatment, and disposal processes. The transportation and collection processes have been found to have minimal impacts relative to other processes [13] and was therefore excluded from this study. The computations assumed an ideal 100% separation efficiency of recyclables and organics at the source. Currently, a fraction of the recyclable waste in UAE is segregated in MRFs (32% of total waste) and diverted from landfills [14]. Based on the literature, 90% of the proposed waste in an incinerator facility is assumed to be recovered as heat and gas, whereas the remaining 10% is converted into ash and disposed of at a landfill. The heat produced by incinerators is used to generate electricity through steam turbines.

The current waste management scheme was set as the business as usual (BAU) strategy compared to the proposed alternative waste management strategies in Figure 1, as follows:

- **Strategy ER:** The strategy constitutes single-bin collection of commingled waste that was processed at an incineration facility. The recovered heat was used to generate electricity, whereas the produced ash was disposed of in an inert landfill.
- **Strategy MR:** The strategy constitutes separate collection in two bins (recyclables and commingled waste). The separated recyclables are sent to an MRF, where the recovered
materials are baled and marketed. The non-recovered materials at the MRF are disposed of in a landfill.

− Strategy MER: The strategy constitutes separate collection in two bins (recyclables and commingled waste). Recyclables are sent to an MRF, whereas MRF rejects are processed at an incineration facility. The produced ash was disposed of in a landfill.

Figure 1. Proposed integrated waste management strategies

2.2. Life Cycle Inventory
The specific waste characteristics in UAE, such as composition and energy content, as well as the local market and operation parameters, particularly those related to energy consumption, are used in the LCI [5]. As reliable local data are limited, the Ecoinvent database was utilized to quantify the energy, resource use, and emissions of the involved processes and materials. The LCA software used in this study, WRATE, is specialized for waste management projects, and comprises an embedded database compiled from actual waste management facilities throughout the world.

2.3. Life Cycle Impact Assessment
The study covers the environmental impact categories which are considered significant and depict a wide range of environmental issues in the UAE. The environmental impact categories investigated are global warming potential (GWP), abiotic depletion potential (ADP), acidification potential (ACP), freshwater aquatic eco-toxicity potential (FAETP), human toxicity potential (HTP) and eutrophication potential (ETP). The environmental impacts are computed through the Problem Oriented Approach, known as the CML methodology [15]. The CML method has equivalence unit and normalization factor for each characterization impact assessment.

2.4. Interpretation
The results of the environmental impact assessment for various waste management strategies are comparatively analysed and interpreted compared to the literature.

3. Results and Discussions
A comparative LCA is carried out for four alternative waste valorization strategies to evaluate the various material/energy streams and the overall environmental burdens in terms of different impact categories. Figure 2 illustrates the main technical aspects, including total energy recovered, various waste streams (recovered, recycled, and landfilled) and the land intake. Waste landfilled is a sum of biodegradable and non-biodegradable landfilled waste. The BAU strategy had the largest...
biodegradable landfilled waste stream of 2.1 Mt, whereas the lowest amount occurred in two strategies: ER (zero due to complete incineration) and MER (zero when MRF rejects were incinerated and ~200 kt when rejects, particularly paper, were landfilled). The materials recovered through recycling offset the consumption of raw materials and associated extraction and production processes. As material recovery is essential in sustainable waste management, the amount of recyclable materials recovered in the two strategies involving MRFs was identical at the maximum possible amount (~5.2 Mt), compared to ~1.7 Mt recycled in the BAU strategy (Figure 2). The BAU and MR strategies did not include any controlled conversion process, i.e., no energy was recovered. Higher amounts of incinerated waste materials lead to the recovery of more energy with the waste management strategy. Figure 2 shows that ER strategy increased the energy produced by 90% compared to MER strategy due to the high energy yield of the recyclables, particularly paper & plastic materials. Strategy MER has the largest land intake since an inclusive land is required for the construction and operation of both MRF and incinerator facilities.

A comparative LCA was performed for four strategies to evaluate the various environmental burdens through six impact categories: GWP, ACP, ETP, FAETP, HTP and ADP. The GWP represents the combined effect of GHGs (CO₂, CH₄, N₂O, CO, CFCs, HCFCs, and HFCs) which can absorb heat radiation and consequently increase the atmospheric temperature. As shown in Figure 3, BAU strategy displays the highest GWP (~520 kg CO₂ eq.). This agrees with the main findings of LCA studies conducted in developed and developing countries, e.g., Lithuania, Thailand, Brazil, USA, and UK which specified that landfilling practices would constantly show a lower environmental performance unlike other conversion systems [16–20]. As burning plastics contributes to the GWP, the high calorific value results in more energy recovered, thus offset significant emissions from electricity that could have been generated in conventional power plants. The GWP caused by incineration depended on the feedstock fed to the incinerator; the GWP contribution was slightly higher in the ER strategy rather than MR and MER strategies, in which high-energy plastics, were combusted rather than recycled. A larger amount of recycled materials resulted in a lower GWP, as can be observed for MR and MER strategies.
ACP is caused by the release of hydrogen ions to the environment through acidifying substances (SO$_2$, NO$_x$, HCl, and NH$_3$). The acidic gases released are washed out by atmospheric precipitation forming acid rain which has widespread noxious effects on plants, soil, and surface waters. ACP is also harmful for human health, especially on the respiratory systems, as well as the degradation of various assets and valuable landmarks. This later impact is of great importance to the UAE as the local non-oil economy is based on real estate and tourism. Acid gases typically emitted from incineration processes to some extent increased the ACP, which was not significantly offset by the energy recovery, and mainly related to the flue gas treatment process. The two strategies involving MRFs showed a positive impact on ACP mainly due to the recovery of materials and the avoided emissions during extraction and production. The ER strategy caused ACP impact ranging from -0.14 to -2.40 kg of SO$_2$ eq., primarily due to NH$_3$, NO$_x$, and SO$_2$ emissions.

ETP comprises all the potential impacts with high environmental levels of macronutrients, (mainly N and P), in aquatic and terrestrial ecosystems. This increases the production of aquatic plants and reduces water quality and oxygen depletion in the bottom layers. For incineration, gases such as NO$_x$ from waste combustion contributed to much of the impact. ER strategy was the highest contributor for ETP by 0.05 kg of PO$_4$ eq. Strategies that involved MRF facilities showed low impact, and the lowest ETP impact was depicted in MRF strategy with a value of -0.10 kg of PO$_4$ eq. followed by MER strategy with half the value.

FAETP measures the relative impact of toxic substances on the freshwater aquatic environment due to the emissions to environmental compartments air, freshwater, seawater, agricultural, and industrial soil. As shown in Figure 3, a positive favourable FAETP impact on the environment was depicted in ER strategy by -8.34 kg 1,4-DCB-eq, mainly due to Barite, Zinc and Vanadium. Whereas the highest FAETP contributor was depicted in MER strategy by 8.32 kg 1, 4-DCB-eq. BAU strategy showed FAETP impact since the areas near landfills have a greater possibility of groundwater contamination because of the potential escape of metals in leachate discharge.

HTP is related to the negative effects of toxic substances (e.g., volatile organic compounds, particulate matter, heavy metals, NO$_x$, SO$_2$) from the waste management process affecting the biological human system (i.e., excluding workplace exposures). All strategies contributed to a positive HTP impacts on the environment, i.e., reduced negative effects of toxic substances. The highest reduced HTP impact was in ER strategy with a value of -60 kg 1, 4-DCB-eq and the lowest reduced impact was in the baseline strategy by -8.76 kg 1, 4-DCB-eq. This was contradicted with a LCA study that stated HTP emissions in incineration was 134 times greater than in landfill due to the air emission of dioxins.

Figure 3. Environmental impact categories of the proposed strategies.
during incineration [20]. MRF and MER strategies presented reduction in HTP impact (~49-52 kg 1, 4-DCB-eq) due to Chromium, PAH, Arsenic, Nickel in air compartment and Barite, PAH, Vanadium ions in water compartment.

ADP is defined in terms of the annual rate of depletion of the stock of minerals and fossil fuels relative to ultimate reserves. Like HTP, all strategies contributed to positive ADP impacts on the environment, i.e., reduced negative effects of resource depletion. The main savings were due to the replacement of fossil fuels; thus, the strategies with more landfiling gave the worst results. Strategies that involved MRF facilities showed a lower ADP impact mostly due to coal, natural gas, crude oil, and molybdenum (0.11% in sulphide, Mo 0.41%, and Cu 0.36% in crude ore). The highest reduced ADP impact was in the MER strategy, with a value of -8.89 kg Antimony-eq. Also, the ER strategy had a positive ADP environmental impact due to the electricity generated by the process.

4. Conclusion

Material and energy recovery technologies can potentially make a substantial contribution to renewable energy production in the UAE while alleviating environmental impacts associated with landfiling. This study discussed the six environmental impacts: GWP, ADP, ACP, FAETP, HTP and ETP of selected MER-based strategies as alternatives to conventional landfiling. Combining MR and ER was the optimum environmental option for the management of recyclables in terms of GWP and ADP. The ER strategy presented a positive favourable FETP and HTP impacts yet showed the worst environmental impact in terms of ACP and ETP. On the other hand, the MR strategy showed positive ETP and ACP impacts, i.e., mainly due to the recovery of materials and the avoided emissions during extraction and production. The baseline landfiling strategy was the least environmentally favourable compared to the examined waste valorization systems.

5. References

[1] SCAD 2018 Waste statistics Abu Dhabi waste management centre
[2] EAD 2016 Waste and environment annual report
[3] Abdallah A, Shanableh A, Arab M, Shabib A, Adghim M and El-Sherbiny R 2019 J. Environ. Manage. 232 58-65
[4] Shabib A and Abdallah M 2020 Int. J. Environ. Stud. 7233
[5] Mendes M, Aramaki T and Hanaki K 2004 Resour. Conserv. Recycl. 41 47-63
[6] Burnley S, Coleman T and Peirce A 2015 Waste Manag. 39 295-304
[7] Buttol P, Masoni P, Bonoli A, Goldoni S, Belladonna V and Cavazzuti C 2007 Waste Manag. 27 1059-1070
[8] Tunesi S 2011 Waste Manag. 31 561-571
[9] Liamsanguan C, Gheewala S 2008 J. Environ. Manage. 87 132-138
[10] Demetrious A, Crossin E 2019 J. Mater. Cycles Waste Manag. 21 850-860
[11] Wang M, Li Z, Chen L, Liu P, Zhang R, Liu W, Ma Y, Wang Y and Li X 2020 Environ. Sci. Pollut. Res. 27 42158-42167
[12] ISO 2006 Environmental management life cycle assessment-principles and framework Environmental Management System Requirements
[13] Abdallah M and Elfeky A 2021 J. Environ. Manage. 280 111839
[14] Abdallah M, Shanableh A, Shabib A and Adghim M 2018 Waste Manag. 82 207-219
[15] Tawatsin A 2014 Environmental assessment of waste to energy processes specifically incineration and anaerobic digestion using life cycle assessment
[16] Miliute J and Kazimieras Staniškis J 2010 Waste Manag. Res. 28 298-308
[17] Cleary J 2009 Environ. Int. 35 1256-1266
[18] Emery A, Davies A, Griffiths A and Williams K 2007 Resour. Conserv. Recycl. 49 244-263
[19] Kaplan P. O, Decarolis J and Thorneloe S 2009 Environ. Sci. Technol. 43 1711-1717
[20] Leme M. M. V, Rocha M. H, Lora E. E. S, Venturini O. J, Lopes B. M and Ferreira C. H 2014 Resour. Conserv. Recycl. 87 8–20

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