Article

Deploying Municipal Solid Waste Management 3R-WTE Framework in Saudi Arabia: Challenges and Future

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Abstract: The need for resilience and an agile waste management system in Saudi Arabia is vital to control safely the rapid growth of its municipal solid waste (MSW) with minimal environment toll. Similarly, the domestic energy production in Saudi Arabia is thriving and putting a tremendous pressure on its huge reserves of fossil oil. Waste to energy (WTE) plants provides a golden opportunity for Saudi Arabia; however, both challenges (MSW mitigation and energy production) are usually looked at in isolation. This paper at first explores the potential of expanding the WTE energy production in the eastern province in Saudi Arabia under two scenarios (complete mass burn with and without recycling). Secondly, this study analyzes the effect of 3Rs (reduce, reuse, recycle) practices implementation in a residential camp (11,000 population) to influence the behavior of the camp’s citizens to reduce their average waste (kg/capita). The results of the 3R-WTE framework show a potential may reach 254 Megawatt (MW) of electricity by year 2030. The 3R system implementation in the camp reduced MSW production from 5,625 tons to 3000 tons of household waste every year, which is considered lower than what the surrounding communities to be produced in the same area.

Keywords: municipal solid waste (MSW); 3R-WTE; solid waste management; sustainability evaluation; waste-to-energy (WTE); Saudi Arabia

1. Introduction

Currently, the municipal solid waste (MSW) generated around the world is on the rise reaching about 2.01 billion tons annually [1], which is forecasted to reach 2.59 billion tons by the end of 2030. Due to the increase in the levels of global urbanization growth and population at a much higher rate, the rate of MSW generation is projected to keep rising to a rate of 1.24 kg/capita/day by the end of 2025 (used to be 1.2 kg/capita/day in 2012) [2]. Having such numbers will indeed mount a huge burden on authorities to develop efficient waste management policies that can cope with the increase in MSW generation. The obligation of governments is critical as not solving the MSW accumulation will distress the economic growth of the country, environment, and health of citizens.

The literature addressed the consequences of the MSW accumulation twofold: MSW economic, and environment and health. Economic effect may put a burden on the government budget to collect and treat MSW, which contributes a large deduction of local country budget and hence, urban waste management and control is expensive. Kaza et al. (2018) [1] stated that for many low-income countries, waste management and control comprises around 20% of municipality budgets and waste treatment and mitigation accounts for almost 4% of municipality budgets. Similarly, Hoornweg et al. (2012) [3] forecasted that cost of managing and controlling waste in developing countries will increase from...
about 20 billion USD in 2010 to 80 billion USD by the end of 2025, while in less developing countries, the rate of increase is expected to follow higher rate. Thus, Hoornweg et al. (2012) [3] emphasized the need for less developing countries to act seriously in finding sustainable solutions for managing and controlling MSW. Alternatively, Vergara and Tchobanoglous (2012) [4] studied environment and health consequences of uncollected MSW or poorly MSW disposal. Such poor MSW practices can significantly affect public health and environment and ultimately increase the healthcare and environment protection bills. More importantly, poor MSW practices may lead to climate change due to the significant amount of greenhouse gas (GHG) emissions generated e.g., the waste steam organic friction radiates the methane, as well as water, land, and air pollution [3–6]. Improper MSW management leads to numerous problems for environment, occupational health [7], harmful gases [8], bioaerosols, and dust [9].

MSW management involves the activities and processes needed to manage solid waste from its initiation to its final stage [10], including collection of waste, transportation, treatment and disposal, and monitoring and controlling of the waste management process [11]. MSW management should integrate proper technology selection, working environments, and establish a ‘social license’ between the governments and local community [12]. MSW management is linked to circular economy [13] through enhancing the value of products to be maintained on the market for a long period of time and, hence, minimizing waste [14].

Several MSW management technologies have been applied to alleviate risks on health and environment; however, landfilling is the most common utilized MSW management technology. Yet, landfilling leachate causes soil contamination and harm the underground and surface water. However, the contamination can be controlled by effective design of landfill structure to isolate the trash from the surrounding environment [15,16]. More recent MSW technologies emerged such as mechanical–biological treatment (MBT) for managing uninsulated organic waste. MBT is the combination of both physical and biological operations, which can be managed in several ways [17]. Composting is another aerobic technology of separating the components of organic material wastes by degrading the organic material under aerobic conditions, producing sanitized and stabilized fertilizer products. Composting contributes to decrease GHG emissions [18], improve the soil quality [19], and reduce landfill leachate [20]. MBT and composting are advisable MSW technologies because of their contributions to grow economy and keep environment clean. However, MBT and composting are only efficient in cases of low size of MSW generation. Moreover, treating waste using MBT plants may lead to releasing odorous compounds as well as several air pollutants [21].

A more efficient MSW technologies evolved as waste-to-energy (WTE) technologies, which have six strategies, namely: Mass burn, gasification, plasma arc gasification, anaerobic digestion, refused derived fuel (RDF), and solid recovered fuel (SRF). The RDF and SRF are high caloric fractions recovered from combustible components of MSW [22]. In general, the mass burn is the most WTE prevalent technology because its ability to consume a large MSW quantities compare to other bio-related technologies (MBT and composting). Although the waste management concept was initially introduced for reducing waste volumes and maintaining public hygiene, it has evolved to encompass the waste prevention, waste recycling, and waste-to-energy (WTE) [23]. Nowadays, waste management mainly encompasses a wider spectrum to include the regular MSW management activities, mitigating environmental damage and generating electricity [24]. Waste-to-energy (WTE) mass burn strategy is the most competitive method to convert the material waste into a useful type of energy [25]. The mass burn can be combined with recycling technology to achieve better efficiency, which requires low capital and operational costs and has high efficiencies. Performing mass burn with recycling involves an initial stage at which the waste is segregated into recyclable and non-recyclable contents. Those materials that cannot be recycled are passed through for mass burn [26]. The complete mass burn has the advantage of reducing waste by 80% and mass by 70% and relatively lower cost in comparison to other technologies [27]. Additionally, they can handle all types of waste including organic materials and requires low level
of technology and human resource skills. After considering the losses in the technology, the overall efficiency of this technology is about 25% [26].

Developing countries do not yet have a system for managing MSW generation, and they still use open landfills method for MSW disposal [28]. Unfortunately, the Middle East and other developing countries in Asia and Africa lack efficient integrated waste management systems. Poor MSW management systems suffer from inadequate working conditions, budget restrictions, insufficient accurate apparatuses for governance, improper and unsuitable selection and application of technology, poor consciousness, and are dependent on imported tools and goods. Poorly managed and controlled the waste has various effects on environment, health, and economy. Therefore, it is vital to establish resilient and sustainable waste management practices to diminish the amount of waste generation at source and residential areas by educating local citizens to enhance their awareness of waste sorting [29], and implement appropriate policies and strategies for managing and achieve benefits of the generated waste.

The aim of this research is to evaluate and assess waste management practices in Saudi Arabia. The suggested MSW system in this paper is composed of a blend of two strategies. First, to control and minimize the size of produced MSW in residential camps by educating residents and providing the concept of 3Rs (reduce, reuse, and recycle). The second part of the framework is to explore the potential of WTE mass burn strategy to be deployed in the eastern province of Saudi Arabia.

The suggested framework, named 3R-WTE, is implemented to reduce the wasted generation rate by awareness campaigns and recycling programs at the level of local community and to generate energy (mass burn WTE technology). It goes without saying that recycling and waste reduction have numerous environmental benefits, namely: Reducing waste save energy, conserving natural resources, limiting pollution, and supporting several sectors of the economy and many other countless benefits. Local communities may adopt “3Rs” programs (i.e., “Reduce”, “Reuse” and “Recycle”). Such initiatives at the local community level can be extended to larger populated areas, which ultimately help to reduce the amount of waste dumped in landfills and save the environment, natural resources, and our planet.

2. Materials and Methods

The focus of this research is on the potential use of WTE plants to generate electricity and also the role of educating population on the important role of residential waste mitigation. Although much research can be found on combined WTE along with waste mitigation initiatives, less consensus in naming such initiatives is witnessed in the literature as concluded by [13]. Perhaps the use of the 4R framework (reduce, reuse, recycle, and recover), which is at the core of the European Union (EU) Waste Framework Directive (European Commission, 2008) [30], is the most reliable definition of the combined WTE residential waste mitigation frameworks. In our work, we adopt almost a similar definition to the 4R, however, our proposed combined WTE waste mitigation framework differs in that it is in the recovery stage. In the work of [13], addressing Recovery in the 4R framework (pp. 223, Table 2) pertained only to WTE incineration. Therefore, the “recover” is not mentioned, being an essential word given the fact that the research explores the “energy production in the eastern province in Saudi Arabia under two scenarios (complete mass burn with and without recycling)”. As such, we present the 4R framework as “3R-WTE”.

The research team studied the potential of WTE (complete mass burn and mass burn with recycling) utilization in the eastern province of Saudi Arabia. The current demand for electricity is also forecasted until the year 2030 in the eastern province of Saudi Arabia. It also studied the implementation of the 3R (reduce, reuse, recycle) initiative in a residential camp in the eastern province in Saudi Arabia to influence the behavior of the camp’s citizens and reduce the average waste kg capita. The WTE technologies used in this research are complete mass burn and mass burn with recycling. Hoang et al. (2020) [31] studied the “Reducing, reusing, and recycling waste at source” as a viable alternative for MSW mitigation. This approach has been adopted in several cities around the world including India [32], Romania [33], and Vietnam [34,35]. Ferronato et al. (2019) [36] studied
the opportunities and challenges of applying the circular economy model for waste management at two developing big cities i.e., Romania and Bolivia. In our framework, we extend this alternative, named 3Rs, to be combined with the WTE incineration alternative in an MSW disposal system named as 3R-WTE framework as shown in Figure 1. We believe this combination will help planners to disseminate the MSW mitigation practices and improve the efficiency of MSW disposal system as a whole. Figure 1 shows the suggested 3Rs-WTE framework, which was implemented in a residential camp in the eastern province of Saudi Arabia (Figure 2). The case study will mention the collection and disposal methodology and will focus on the best practices that lead to reducing residential wastes and improving recycling.

Figure 1. 3Rs (reduce, reuse, recycle)-waste-to-energy (WTE) framework.

Figure 2. Map of Saudi Arabia showing the Eastern Province.
Saudi Arabia, similar to many other countries, is trying to reduce its dependency on fuel oil burn to produce electricity. However, the population growth of Saudi Arabia mounts a tremendous pressure to produce electricity as it reaches an annual average of 3.4% along 80% urbanization level (population living in cities). Similarly, population growth and urbanization lead to a substantial increase in MSW generation. Currently, Saudi Arabia generates 14 million tons of MSW annually with an average of 1.4 kg/capita/day which is more than the global average of 1.2 kg/capita/day [37]. The total MSW energy generation up to year 2030 is forecasted as shown in Figure 3. The year 2010 was chosen as the base year for forecasting. The energy contents listed in Table 1 are used to determine the total energy content per Kg of waste. The waste composition and energy content for each type of waste for Saudi Arabia is listed in Table 1. The paper also provides a detailed case study about the role of waste generation reduction in an 11,000-person residential camp in the Eastern Province in Saudi Arabia (Figure 2). The data collection for the case depends on published statistics related to population and waste generation in Saudi Arabia. The research team has also conducted field interviews with experts and officers participating in the waste management process. The Eastern Province is the largest province of Saudi Arabia by area with 672,522 km², and it is the third most populous province in Saudi Arabia [38].

![Figure 3](image-url). Net power generation potential (MW) for Eastern Province for the years 2010–2030.

For the aim of forecasting, the year 2010 was chosen as the base year. The daily waste volume rate per person is assumed to be 1.4 kg [39]. Currently, the total population of the eastern province of Saudi Arabia is 5.2 million (Figure 4). The population growth is projected to maintain its historical trend of 3.4%, which is the average growth of population in Saudi Arabia, for the year up to the year 2030, the total MSW generation is forecasted accordingly for the Eastern Province.

Figure 5 reveals the Eastern Province MSW generation forecast results from the year 2010 to up to the year 2030. The figure shows that a huge quantity of waste will be generated by year 2030 (3545 thousands tons), which needs managing properly to reduce its consequences on the environment and health over the long-term.
Figure 4. The Eastern Province population forecast results.

Figure 5 reveals the Eastern Province MSW generation forecast results from the year 2010 to up to the year 2030. The figure shows that a huge quantity of waste will be generated by year 2030 (3545 thousands tons), which needs managing properly to reduce its consequences on the environment and health over the long-term.

3. Results

The 3R-WTE framework is implemented in the eastern province of Saudi Arabia. In this section, the results of implementing the framework will be discussed.

3.1. Forecasting of WTE in Saudi Arabia

The current practices for managing MSW in Saudi Arabia include collecting and disposing MSW in open landfill. It is expected that most of the landfills will exceed their capacities within a few years.
The substantial amount of MSW generation and the rich energy contents reveals the potential of using WTE plants in Saudi Arabia to manage waste [37].

The current practice for Waste disposal in Saudi Arabia includes collecting un-segregated waste from several residential and commercial areas to be sent to an open deserted landfills using a fleet of compressor garbage trucks each with three-person crew (collection trips twice a day). Even though it is expected that most of the landfills will exceed their capacities within a few years, disposal of waste in open landfills is still the dominant method due to land availability and the relatively low cost of resources. Currently, in Saudi Arabia, less than 15% of the collected MSW is recycled informally by scavengers who manually extract paper, metals, and plastics [23].

Saudi Arabia is experiencing an increase in domestic oil consumption, which accounts for more than 25% of its oil production [37]. This domestic consumption is expected to increase on a yearly percentage of 3.4% as a result of population increase. Indeed, this will mount more pressure on the infrastructure and challenge the current practices in municipal services especially in MSW collection and disposal. The best strategy is to maximize clean disposal of waste and, simultaneously, mitigating the waste generation rate at residential areas from the first place (kill the problem before it happen). For clean waste disposal, Saudi Arabia started to adopt recent technologies other that land filling in deserted areas.

Even though Saudi Arabia is the second highest oil producer worldwide, it is one of the largest oil consumers [40]. Saudi Arabia has set a plan to utilize nuclear and renewable energy sources including WTE plants to generate 54 Giga Watt within two decades [41]. Deploying WTE plants on a large scale will surely resolve the waste management challenges and will also contribute to energy generation. The high level of population growth along with an increase in the urbanization level of Saudi Arabia have led to substantial increase of MSW generation.

Definitely, WTE practices will serve this target and the need of waste disposal. Concisely, Saudi Arabia is planning to generate energy from using WTE to satisfy 3% of the growing domestic forecasted demands by year 2030; 120 Gigawatts (GW). Emerging technological advancement for managing MSW such as WTE plants will lead to sustainable MSW management [42].

The focus of this section is on the potential use of WTE plants to generate electricity and also the role of educating population on the important role of residential waste mitigation. Saudi Arabia is trying to reduce the dependency on its oil reserves to produce electricity. The WTE technologies used in this research are complete mass burn and mass burn with recycling. In the following is a brief description of various types of WTE technologies.

The Eastern Province occupied first place among the regions of Saudi Arabia regarding the number of power plants and reached 36 power plants, followed by the Western Region with 25 stations, and the central region reached 13 plants. The region with the lowest number of power plants in Saudi Arabia is the southern region with six generating stations, indicating that the eastern region has several power plants and also serves the capital Riyadh in its generation.

The rates of energy consumption vary from one region to another according to the consumption of economic sectors, where the percentage of consumption in the eastern region was the highest for industrial consumption, while the central region is the largest in government consumption, followed by the western region with the highest in the proportion of commercial consumption. The Eastern Province is one of the most important areas of Saudi Arabia from the industrial side and there are large-scale industrial oil and petrochemical companies, factories, and industrials, which largely consume high amounts of electricity.

Saudi Arabia has a very harsh environment where the temperature may reach as high as 50 °C in the shade in mid-summer and may reach 0 °C or even lower in the winter. The high variation in temperature produces a sharp variance in electricity demand over the year, resulting mainly from the high demand for electricity for air conditioning during the hot weather season [43]. The increasing demand for electricity has been met through gas, crude, and heavy oil-powered plants. In the long term, to address the demand issue and reduce the reliance on fossil fuels, the government established
the King Abdullah City of Atomic and Renewable Energy (KACARE) with the aim to utilize the indigenous renewable energy resources through science, research, and industry. The ambition of KACARE program is to generate 72 GW energy from renewable energy sources such as solar, wind, nuclear, and waste-to-energy (WTE) by 2032 [44]. On the other hand, the electricity sector in Saudi Arabia faces many issues that jeopardize sector sustainability, including aging power plants and low electricity tariff [45].

Table 1 shows the Saudi Arabia waste compositions [46] along with energy contents for each type of waste. The third column represents the caloric energy content of the various types of waste [47]. These measures were used to calculate the total energy content per kilogram of Saudi Arabia’s MSW as lower heating value (LHV) listed in column four [48,49]. The energy contents demonstrate the energy generation potential from MSW. To calculate the electricity generation potential, the lower heating value of the solid waste after excluding the organic materials is calculated using energy content of different types of wastes listed Table 1.

### Table 1. MSW energy contents and Energy content of different types of wastes [46–49].

| Material | Waste Composition (%) | Energy Content in Material (kWh/kg) | Energy Content in Waste (kWh/kg) LHV |
|----------|------------------------|-----------------------------------|-------------------------------------|
| Paper    | 28.5                   | 4.39                              | 1.21                                |
| Plastic  | 5.2                    | 9.05                              | 0.46                                |
| Glass    | 4.6                    | 0.00                              | 0.00                                |
| Wood     | 8.0                    | 4.73                              | 0.24                                |
| Textiles | 6.4                    | 5.20                              | 0.22                                |
| Organic  | 37.0                   | 1.55                              | 0.10                                |
| Others   | 10.3                   | 3.36                              | 0.28                                |
|          |                        | Total energy for mass burn with recycling (kWh/kg) | 0.38 |
|          |                        | Total energy contents of complete mass burn (kWh/kg) | 2.51 |

Note: The values assume the separate collection rate and separate collection quality index [50] to be 100%.

For complete incineration techniques, the average lower heating value of the total waste is considered, while for a mass burn with recycling, the recycled products (paper, plastics, glass, wood, and textile) were excluded from the calculations. The energy recovery potential (ERP) in (Gigawatts/day) and net generation potential (NPG) in MW are given by Equations (1) and (2).

\[
\text{ERP} = \frac{\text{dry waste (tons/day) \times LHV (kwh/kg)}}{1000} \quad (1)
\]

\[
\text{NGP} = \eta \times \text{PGP} \quad (2)
\]

where \( \eta \) is the efficiency of the technology where the efficiency for mass burn is taken as 25% [51]. The net power generation potentials were projected for complete mass burn and mass burn with recycling. Figure 2 reveals a potential to generate 254 and 38 Megawatts (MW) of power from MSW using complete incineration and mass burn with recycling.

The peak electricity consumption per capita along with the electricity consumption per household in Eastern Province has been forecasted as shown in Table 2 [52]. The electricity consumption is expected to reach about 15,321 kwh in 2030 with an average growth rate of 3.35% per year [52].

The average number of people per household in Saudi Arabia is 5.6 people [53,54]. The forecasted power generated using the complete incineration and mass burn with recycling would be enough to supply energy to 25,951 and 3882 households in the year 2030, respectively.
Table 2. Electricity demand forecast 2010-2030 and number of households that would be supplied by the energy produced from the two WTE scenarios.

| Year | Per Capita Consumption (Kwh) | Per Household Consumption (Kwh) | Number of Households |
|------|-----------------------------|---------------------------------|---------------------|
|      | Complete Mass Burn | Mass Burn with Recycling |
| 2010 | 7918                       | 44,340.8                      | 29,852               | 4349   |
| 2015 | 9346                       | 52,337.6                      | 29,478               | 4354   |
| 2020 | 11,011                     | 61,661.6                      | 28,717               | 4264   |
| 2025 | 12,994                     | 72,766.4                      | 27,707               | 4096   |
| 2030 | 15,321                     | 85,797.6                      | 25,951               | 3882   |

3.2. Case Study 3Rs: How to Reduce Waste in a Residential Camp

This case study focuses on owned residential camp for a company located in the eastern province of Saudi Arabia, particularly on a waste management system by collecting and disposing of MSW. Also, this case includes best practices and initiatives towards improving the waste management system to further capitalize on the outcomes to recommend the adoption and implementation of such waste management systems to the surrounding within the eastern province of Saudi Arabia.

This company is selected since they have good infrastructure and stewardship environmental reputation, including strict regulations within their premises. This residential camp was constructed for the company employees and their families with all the necessary facilities, including schools, hospitals, and recreation. These are to ensure all living standards are available and meeting their expectations to allow them to spend more time in their jobs while caring for the employees’ families.

This residential camp has dedicated functions to be responsible for the camp, such as gardening, sanitation (accountable for waste management system), pest control, recreation, food, maintenance, and utility services. These are to serve the community to maintain community services facilities and housing units in a safe, environmental, cost-effective, and quality manner to be a desirable place to work and live in. This community has a total of 580,333 square meters of residential area, and more than 11,000 of residents living in the camp. The 3R program started in 1993. Since then, the MSW generation rate is mitigated remarkably compared to other neighborhoods. Currently, the residential camp produces around 3000 tons of waste every year, which is considered lower than what the surrounding communities produce in the same area (eastern province). This reduction credit goes back to the intensive programs, initiatives, and best practices that this camp is investing in. During this awareness program, the camp has mentioned several advantages of reducing the use of plastic bags as listed below:

- Plastic bags kill thousands of marine animals who have mistaken the floating bags for food.
- Plastic bags that get buried in landfills may take over 700 years to decompose.
- Improperly disposed plastic bags contaminate solid and water.
- The production of plastic bags consumes millions of gallons of oil that could be used for fuel and heating.

3.2.1. Collecting and Disposing of Residential Wastes

This residential camp still practices the same way of collecting and disposing of the residential waste in the eastern province of Saudi Arabia, as mentioned earlier in the paper, where landfills are the last place of disposal, but they keep the waste segregated from recyclables and non-recyclables. The non-recyclables are sent to owned landfills by the residential camps, and the recyclables are being used in recycling programs. Moreover, the camp is intensively investing in waste reduction awareness and implementation and recycling programs and initiatives, which will be covered in a separate section. While practicing the same way of waste collection, the camp organized the collection operation to help ensure a clean and healthy community environment by introducing a garbage collection plan.
The garbage in all residential areas is collected daily at 7:00 am from the designated curb at the back alley outside the houses. This helped the camp to facilitate the garbage collection in addition to the tips that are introduced by the camp to be adhered by the residents as mentioned in the following trash tips:

- Garbage must be in plastic bags that are securely closed.
- Bags and garbage drums should be placed on the designated curb or in the back alley outside the houses by 7:00 am on the morning of collection. Please do not leave garbage bags on the curb overnight! Residents should collect drums immediately from the curb to prevent them from blowing away during windy days.
- Remember to store your garbage drums out of sight. Each house has a designated area for holding garbage (inside the house, garage, or in the yard).
- Residents of studio apartments and other areas using centrally located trash stations should deposit their securely closed garbage bags into the metal drums located within the stations.
- For oversized garbage loads such as packing material, debris, garden/tree trimmings, etc., we can arrange a special collection, please contact sanitation unit for assistance.

3.2.2. Recycling and Reducing Wastes Programs and Initiatives

The residential camp has a dedicated recycling group that takes care of recyclable materials from wastes such as plastics, aluminum/metal, and paper for the company offices and residential areas. This group has established its mission, services, and values as the following:

- Mission: We are committed to creating awareness of recycling and its benefits to the community by conducting appropriate campaigns and advertisements.
- Services: Recycle bin collection, school campaigns, and community outreach programs.
- Values:
  - Caring: It is the whole team that counts.
  - Learning: We are recycling our knowledge.
  - Inspiring: We are here to make a difference.

The recycling group timeline history since it was created as below:

- 1993: Paper recycling program initiated.
- 2002: Toner cartridge recycling program initiated.
- 2006: Plastic, glass, and aluminum recycling program begins.
- 2008: Partnerships developed to extend the program to local communities.
- 2011: Major increase in residential participation rates.
- 2012: Moving forward plans for establishing a waste management facility including material recovery facility (MRF) and composting plant.
- 2014: Launching the recycle to transform program.
- 2015–Up to date: Currently, working in broadening the recycling awareness efforts to reach both inside and outside the company’s residential camp and offices.

Recycling Collection

The camp has provided four different bin liners in order to segregate the recyclable wastes and are distributed among the residential and offices as follows:

- Aluminum-Yellow Bin: Used for collecting aluminum cans and metallic food tins/containers (but they should be cleaned first).
- Paper-Blue Bin: Used for newspapers and magazines and stationery-type paper (e.g., office paper, old letters, printer, paper, school work), and post cards, greetings cards and envelops, and cardboard.
Plastic-Green Bin: Used for plastics bottles and lids (e.g., water bottles, milk and fizzy drink bottles, spray bottles, shampoo bottles, ketchup, yoghurt drinks, plastic pots (yoghurt pots), plastic bags

Printer Toners Cartridges: Available in offices and in the center supermarket of the camp for the residential.

In 2018, the camp collected around 149 tons of paper (with a separate collection rate of 46%) for recycling, which is equal to saving 2531 trees. In addition, 191 tons of plastic were collected for recycling with a separate collection rate of 54%. On the other hand, the below are not included in the recycling program and considered as part of the waste that sent to the landfills: Dirty paper such as tissues or wrappers, juice cartons (tetra Pak type), pizza boxes, disposable paper coffee cups, glass ovenware and ceramics, glass jars, bottles and containers, light bulbs, and batteries.

Towards Greener Offices (Recycle Me) Awareness Campaign

The camp has initiated an awareness campaign by introducing the theme “Reduce”, “Reuse”, and “Recycle” along with steps towards greener office spaces as mentioned below:

- Reduce:
  - Think before you print—do you really need to print that?
  - Print on both sides of paper when you can.
  - Remember to print only page you need from a document.

- Reuse:
  - Say NO paper cups—bring your own mug or ceramic/glass cups for water, coffee, and tea.
  - Reuse envelopes.

- Recycle:
  - Paper in blue bin.
  - Plastics bottles in green bin.
  - Aluminum cans in yellow bin.
  - Toner cartridges.

In 2019, the camp used, on average, about 16,380 reams of papers type 80 gms, which is 23% lower than the reams used in 2018. The annual saving cost is estimated to be about 17,000 USD, which represents the cost of the saved reams (3770 reams). It is reported that a tree that is 18 meters tall and about 20 cm in diameter can make 16.67 reams [55] Thus, the camp saves around 226 trees each year.

“Recycle to Transform” Awareness Campaign

The recycling group has initiated the “Recycling to Transform” campaign in the camp’s commissaries. This campaign is designed to increase awareness about recycling and also to encourage the residences to recycle appropriate materials instead of identifying them as waste and throwing them out in the trash.

The recycling group tagged various plastic, glass, and aluminum products with “Recycle Me” tags to remind customers to recycle the containers after their contents have been used. Also, the group distributed reusable bags to the commissary customers and told them about the importance of recycling for the environment. For example, changing a small shopping habit to switch from plastic bags to reusable canvas bags will have huge environmental damage avoidance. According to a report released by European Commission-DG Environment in 2011 titled Assessment of impacts of options to reduce the use of single-use plastic carrier bags, reusable canvas bags are 14 times better than plastic bags and 39 times better than paper bags, assuming that canvas bags get a good workout and are used 500 times during their life cycle. The group has invited volunteers from middle schools to participate in the campaign to enhance the awareness of the coming generations.
Back to School Events

The recycling group participated in an annual back to school events to provide awareness of recycling. The event provided crafts work with kids to work with them physically in some real examples about recycling and did some recycling-related arts. Also, the event provided recycling roll up stands for adults and handed out brochures, information booklets, and giveaways.

Coffee Time Challenge Campaign

This campaign aims to switch the single-use paper cups to reusable mugs the next time you have your coffee/tea at the office or home. The campaign emphasizes on the below benefits:

- Economical: Some coffee shops will charge you less if you bring your own mug.
- Environmental: Using reusable mugs reduces waste. Only 1 out of 400 existing paper cups get recycled [56].
- Health: Hot liquid can cause the plastic polyethylene lining in disposable paper cups to break down and leach into drinks.

The recycling group encourages the residents to be role models in a sustainable lifestyle, environmental stewardship, and promoting zero waste. In other words, every cup counts and small efforts make a big difference; do your part and let us go green.

In 2018, the camp offices saved around 1.51 million 16-ounce paper coffee cups, which is equal to saving 613 trees. In 2006, the USA used 6.5 million trees to make 16 billion paper coffee cups [57].

Recycling Activities on Earth Day

One of the recycling group’s objectives is to promote the concept of recycling and environmental stewardship among our youth in the camp schools by organizing recycling-themed fun activities.

A total of 533 students (aged from 2–14 years old) in camp schools took part in the games and art competition to commemorate the Earth Day 2019 celebration. There were 247 entries from camp schools in the recycling art competition, in which participants were required to design a poster that encourages recycling or to create a model with recyclable materials based on the given criteria. The winners received prizes and certificates. Also, presentations and other fun activities were conducted.

Reuse of Discarded Wood

In support of the camp waste management initiatives, the recycling group has applied a new practice in the camp, which is the reuse of discarded wood. The used wooden pallets were transformed into new planter boxes as shown in Figure 6. This initiative of upcycling waste wood minimizes the material costs and even reduces the waste that is being dumped into landfill sites.

![Figure 6. Reuse of discarded wood as planter boxes.](image-url)
In 2019, the camp residents transformed around 9 tons of discarded wooden pallets into 1200 planter boxes. It is estimated that the cost of raw material to produce the planter boxes is around 14,400 USD. According to a previous study [46], the disposal cost per ton of MSW in Saudi Arabia is 151.2 USD. Thus, the cost of disposing the collected discarded wooden pallets would be around 1360 USD, which can be considered as a saving since the camps residents transformed discarded wooden pallets into valuable products instead of sending them to landfills as waste.

Innovative Waste Reduction Initiatives

A wood chipper or a tree chipper is a machine used for reducing wood (generally tree limbs or trunks) into smaller woodchips as shown in Figure 7. The benefit of this is to minimize the waste in the community, and at the same time, the woodchips can be used in landscape or soil fertilizer.

![Figure 7. Tree chipper and woodchips.](image1)

Additionally, it reduces the volume of the “tree trimming waste” by up to 40%, saving on transport, time, and ultimately reducing the number of loader trucks used for landfill trips.

Upcycling Old Tree Trunks

Upcycling, also known as creative reuse, is the process of transforming by-products, waste materials, and unwanted products into new materials of better quality or environmental value. The upcycling old tree trunks initiative will take care of old conocarpus trees that were needed to be removed from specific areas. Instead of dumping the trunks of the trees, they were converted into a wooden footpath and other furniture amenities at the camp as shown in Figure 8.

![Figure 8. Old conocarpus trees converted into wooden footpaths.](image2)
As a result of adopting this initiative, one conocarpus tree is used to produce 12 square meters of the walkway.

3.2.3. Waste Management System Guidelines and Operations Manual

The camp management has established its own guidelines and operations manual to govern the waste management system in line with the Saudi Government environmental standards by the Presidency of Meteorology and Environment (PME) and the U.S. Environmental Protection Agency. These guidelines and manuals are considered best practices when compared with the local practices. In the future, they may be adopted and implemented by the Municipality in the eastern province. This paper will focus on the recycling collection services that are performed by the residential camp.

Empty Aluminum Can Collection Services

The recycling crew shall remove empty aluminum cans from specially designated steel and plastic refuse drums and replace lids on drums after emptying. The crew shall load cans, including those transported from collection areas (designated bins), onto contractor-furnished trucks for transportation to recycling plants in Dammam/Al-Khobar areas. The crew shall ensure contents are secured and remain so during transit.

The recycling crew shall also load a specially designated steel lugger box for empty aluminum cans from locations assigned by the supervisor onto a contractor-furnished lugger load truck and transport to recycling plants in Dammam/Al-Khobar areas. The crew shall ensure contents are secured and remain so during transit.

Laborers shall pick up all overflow of empty cans and refuse and clean spilled beverage and food from an area within a radius of four (4) feet around the drum/lugger box. The area shall be cleaned by scraping spilled substances from the soil with a shovel. If a drum sits on concrete, asphalt, or other pavement/floor, spilled beverage and food shall be cleaned from the pavement/floor by wet mopping with a detergent solution. Pick-up and cleaning functions shall be conducted each time a drum/lugger box is serviced.

Aluminum cans and plastics from designated drums are picked up daily by the recycling contractor trucks to be brought to the segregation area. These are then delivered to the recycling factory by the recycling trucks under the miscellaneous clearance services. The miscellaneous recycling trucks collect the aluminum cans and plastics directly from the recycling lugger boxes. They are transported to the segregation area and then proceed to delivery at the recycling factory.

Central area contractor shall collect money from recycling plants and deposit with the camp management.

Paper/Cartons Collection Services

Recycling crew shall load four (4) cubic yard steel lugger boxes and/or steel/plastic drums for paper/cartons from areas designated by the site supervisor onto a contractor-furnished lugger load truck and transport to recycling plants. The crew shall empty and return the lugger boxes to specified locations; the contractor shall ensure contents are secured and remain so during transit.

Pick up overflow materials form area within a radius of four (4) feet around a lugger box. The area shall be kept clean. Pickup and cleaning functions shall be conducted each time a lugger box is serviced. Central area contractor shall collect money from recycling plants and deposit with the camp management.

4. Discussion

MSW management systems usually deal with the economic and environmental measures. Nevertheless, the social aspect is overlooked in the MSW management systems on many occasions. This paper shows the role of social practices that complement the economic and environment aspects...
to have a complete sustainable MSW framework, named 3R-WTE, which reduces the waste generation rate by awareness campaigns and recycling programs and to generate energy. The 3R system has been implemented in a residential camp located in the eastern province of Saudi Arabia with a population of more than 11,000 of residents. Several activates have been adopted, as shown above, to control and minimize the size of produced MSW by, mainly, educating residents, such as intensive programs, initiatives, and best practices at the level of local community. As a result, the residents living in the camp produce 3000 tons of MSW per year (around 0.75 kg/capita/day), which is much lower than the Saudi Arabia average of 1.4 kg/capita/day. This amount of waste produced has the potential to generate 0.0785 MW of power, which would be enough to supply energy to around 11 households.

On the energy side, the potential of WTE mass burn utilization in the eastern province of Saudi Arabia is demonstrated and appreciated by research participants. The results show a potential to generate 254 and 38 Megawatts (MW) of power from municipal solid waste using complete incineration and mass burn with recycling, which will be enough to supply energy to 25,951 and 3882 households in the year 2030, respectively.

Indeed, this energy proportion of WTE expected energy production is not large but the social and environment aspects are highly appreciated. In fact, the eastern province of Saudi Arabia can receive MSW from other provinces in Saudi Arabia and utilize them their WTE plants. Such expansion in MSW processing will control the growth of MSW generation in Saudi Arabia, which is estimated to reach 14 million tons of solid waste per year. The large amount of generated solid waste has put enormous pressure on the infrastructure system and environment, which represents a big challenge to the authorities and citizens. Saudi Arabia has a high potential to convert the huge amount of solid waste and simultaneously add value to the economy in terms of energy. The current practices adopted in Saudi Arabia are not effective, thus there is a need to shift toward more sustainable (social, economic, and environmental) waste management approaches to manage solid waste from its initiation to its final stage. One point also worth to mention is that adding such social initiatives and expanding in waste recycling will also open the door for jobs creation and new investment opportunities for private sector in Saudi Arabia. The growth of Saudi Arabia’s population with an average of 3.4% over the last four decades needs jobs creation, private investment opportunities, and MSW mitigation programs, which are surely offered by the 3R-WTE framework.

As a suggestion for future research, this work can be extended by applying the initiatives and programs to larger populated areas, which ultimately help to reduce the amount of waste dumped in landfills and save the environment, natural resources, and our planet. These best practices will reduce the MSW management cost through minimizing the amount of MSW produced in its initiation. Another direction for future research is to use multi-criteria decision-making approaches to find the most sustainable waste-to-energy (WTE) technology to be implemented in Saudi Arabia. Lastly, a study to explore the recycling potential in Saudi Arabia is highly encouraged.

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