Emergy based carbon footprinting of household solid waste management scenarios in Pakistan.

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# Abstract

Waste management is a serious challenge across many resource constrained countries of the world leading to environmental issues such as pollution and high rates of soil occupation, health issues induced by poor hygienic conditions, and financial problems linked to the high costs associated to waste management, which have high impacts on municipal budget. In this study we determined the environmental impact of different waste disposal scenarios in a major city of Pakistan. Existing studies on the subject of waste management in Pakistan fail to account for the environmental burden of waste processing technologies. To counter this, in this paper we used Emergy based accounting procedures to obtain a donor or nature based perspective for environmental footprinting. Three scenarios were considered for the analysis consisting of the current practice of open dumping as Scenario A; sanitary landfilling with composting and material recycling as Scenario B and incineration with composting and recycling as Scenario C. Results were presented in the form of Emergy based input-output tables as well as greenhouse gas emissions as measured in kg CO2 equivalent (kCO2eq/t) per tonne of waste. Scenario A was the worst option due to its high emissions and lack of any useful output. Scenario B was identified as the best alternative as it resulted in similar amount of net emissions as Scenario C but with relatively lower stress on the environment as indicated by the Emergy indicators. In view of the subject city’s resource constraints we recommend inducing waste reduction and minimization practices through public awareness campaigns. Resource contributions from the civic society are also suggested for erecting the necessary waste disposal infrastructure. The results and suggestions presented herein need to be highlighted in a timely manner in order to resolve environmental and public health risks posed by the current practices.

Key Words

Emergy accounting; life cycle perspective; greenhouse gas; emissions; waste disposal.

# Introduction

Waste management is a serious challenge across many countries of the world. This issue is especially significant in the developing countries due to their resource constraints. Such countries lack the technical skills and tools to manage their wastes effectively. Consequently, many of these countries suffer from environmental pollution and associated public health hazards (Ali et al., 2017b). In order to overcome this challenge, it is important to appraise the current situation of waste management in these countries and suggest remedial measures. To this aim, availability of site specific data is quite important (Ripa et al., 2017). Moreover, while a part of the waste management solution can be obtained from the experience of the developed countries, it is important to find local solutions to address this challenge in a sustainable manner. This is especially important as many of the developing countries in Asia and Africa are experiencing rapid urban and demographic transitions (Cobbinah et al., 2015). Currently, eight out of the ten most populated cities in the world are in developing countries in Asia (UNSTATS, 2017) and many of them have poor waste management controls leading to public health hazards such as environmental pollution and contamination (Hardoy et al., 2013). Moreover, secondary cities across many of these countries are expanding rapidly as peri-urban areas are being absorbed into urban agglomerations resulting in an increasing number of cities having million plus populations (Murtaza Haider, 2014). Unfortunately, public infrastructure in these countries is insufficient to feed the growing needs of urbanization (Ali et al., 2016c). Moreover, there is a lack of scientific literature regarding characterization of urban solid waste and the quality of waste management systems in these increasingly significant cities. It is important to identify current issues related to solid waste management in these cities so as to avoid public health catastrophes in the future.

In this paper we will analyze solid waste disposal scenarios in a major city of Pakistan, namely Gujranwala. Pakistan is a resource constrained, developing country in South Asia. It has been experiencing rapid urbanization in its recent history. Currently 37% of the population in the country lives in the cities and this figure is expected to rise to about 50% by the year 2020 (Murtaza Haider, 2014). Infrastructure for municipal waste management in Gujranwala, as in many other Pakistani cities, is insufficient and requires significant overhauling and expansion. Although urban solid waste comes from many streams including municipal, industrial, construction, healthcare and other activities, in Pakistan a major portion of this waste comes from households of which the main portion consists of biomass, such as kitchen waste (Raheem et al., 2016). Most of the municipal solid waste (MSW) in Pakistan is discharged in open dumping grounds and vacant lots without any safety mechanisms (Ali et al., 2016a) and such places are haunted by drug addicts, stray animals and under-age scavengers looking for recyclable items which leads to further epidemiological problems (Rauf et al., 2013). This is due, among other things, to the fact that the country does not have incinerators or sufficient composting or recycling plants for efficient waste disposal. Most of the studies on solid waste management in Pakistan are usually restricted to waste characterization and only few of the existing studies analyze the consequences of different end-of-life waste disposal scenarios on the environment (Batool and Chuadhry, 2009), (Ali et al., 2016a). Moreover, most of these studies are limited to the largest cities in the country including provincial capitals, such as Lahore or Karachi, and secondary cities remain neglected. To fill this important gap in the existing literature, this study will focus on solid waste management challenges in Gujranwala city which has a population of 4.8 million inhabitants at the district level and 2.7 million people in its predominantly urban counties (Punjab Bureau of Statistics, 2015). It is the fastest growing city in the country with an annual growth rate of 3.49% (Mayors, 2011), but unfortunately it is also seen as one of the dirtiest cities in the country with poor waste management controls (Correspondent, 2013). Pathogenic medical waste from different hospitals is often found mixed with general waste and the incidence of infectious diseases in the city borne out of unhygienic practices is higher than the average for the whole country (Ali et al., 2017a). Since the city lies only about 60 Km away from the provincial capital, Lahore, given the current rates of urbanization and population in the future the two cities might become indistinguishable (Arif and Hamid, 2009). It is thus imperative to analyze the waste management situation in the city and suggest measures for improvement. Constant monitoring and evaluation of its waste management practices is also necessary so as to ensure that the city follows sustainable growth. Hence the present study can be used in the future as a reference point for benchmarking, monitoring and comparison purposes. Figure 1 shows the location of the city in the wider geographical setting.



**Figure 1.** Geographical localization of Pakistan and Gujranwala city

# Literature Review

Studies on urban solid waste management usually focus on waste characterization, mass flow analysis and life cycle assessment (LCA) of waste disposal scenarios for the calculation of greenhouse gas (GHG) emissions (Liu et al., 2017). As solid waste collection, transportation and disposal activities consume fossil fuels and therefore contribute to GHG emissions (Friedrich and Trois, 2016), the selection of the waste disposal and treatment technology to apply should be supported by a careful calculation of these emissions. As mentioned earlier, the usual practice in such analyses involves estimation of carbon emissions of different waste disposal scenarios with the aid of an LCA tool (Meng et al., 2016). However, this approach fails to account for the impacts of all the activities related to solid wastes management, encompassing labor, transportation, machinery and natural capital involved. Moreover, LCAs of waste management systems generally cut out the impacts associated to the entire production and consumption chain leading to the waste, since the boundary normally includes only the actual disposal processes (Gala et al., 2015).

In order to get a more holistic perspective, researchers are increasingly turning towards a system’s approach for analysis. Examples of models used for such analyses include social network analysis (Ali et al., 2016b; Caniato et al., 2015), system dynamics (Al-Khatib et al., 2016), data envelopment analysis (Ali et al., 2017c), (Albores et al., 2016) and Emergy accounting (Gala et al., 2015). In particular, in Emergy accounting the boundary is implicitly set at the biosphere level, therefore the entire supply-chain is scanned in spatial and temporal dimension (Gala et al., 2015). Stemming from the work by H.T. Odum (Odum, 1988; Odum, 1996), the concept of Emergy brought to the scientific community a new paradigm aiming at quantifying resources from a *nature‑centred* (or *donor-oriented*) point of view. In its traditional definition Emergy quantifies the amount of available embodied energy (usually expressed as *solar* energy and measured in *solar emjoules* - sej - or its multiples) previously directly and indirectly required to generate a product and/or to support a system and its level of organization (Agostinho et al., 2013; Ridolfi et al., 2008). The concept of Emergy borrows heavily from the thermodynamic concept of Exergy, which it traces during various energy transformations, thus serving to show how the quality of energy changes during various steps in a system (Sciubba and Ulgiati, 2005) (Bastianoni et al., 2007). As stated by (Raugei, 2011) “*Emergy may ultimately be interpreted for all practical intents and purposes as the ‘memory’ of the total exergy that was previously spent to make a product or service available to the end user*”. This means that, “*for human-dominated systems* [...] *more Emergy assigned to a process’ yield should be interpreted* […] *as a larger appropriation of* *past environmental work to produce the used resources and/or more potentially required[[1]](#footnote-1)work to replace them”* (Raugei, 2011). This definition appears to lend itself very well to establish a link between a formal explanation of Emergy and a possible, more practical, interpretation of its “donor side value” (Dong et al., 2008). According to this rationale, the greater the Emergy of a product or a system, the greater the environmental work needed to produce or sustain it (Marvuglia et al., 2013).

One advantage of using Emergy as compared to other sustainability assessment methods, such as LCA, is the use of a common and consistent set of units, thus widening its application to include different systems and processes. This is because different materials and resources can be differentiated on the basis of the quality of energy contained within them during the process that made them evolve into their present state. In other words, Emergy is a useful tool in tracing the material and energy cycling pathways as they are transformed into products, services or waste items. The difference in quality of the consumed resources determines the amount of energy stored into the eventual product or system. This stored energy can be represented in the units of Emergy to help make comparisons and create benchmarks. An additional advantage of using Emergy analysis is that it goes beyond the usual carbon footprinting and it allows to assess the sustainability of the whole system from a nature centric perspective (Almeida et al., 2012) rather than end-user (human-centric) perspective.

Few existing studies on Emergy-based environmental assessment of solid waste management scenarios concern developing countries (Meidiana, 2014) and most of these studies involve industrialized countries such as China, Brazil or other Western countries (Chen et al., 2017), (Liu et al., 2017). For instance, (Agostinho et al., 2013) studied whether there is a net yield on recycling materials in an urban waste recycling plant in Brazil and discovered that Emergy yield increased with recycling rates. (Lei and Wang, 2008) used Emergy analysis to investigate Macao’s waste treatment in 1995, 1999, 2003 and 2004. They concluded that although the city’s municipal wastes contained a significant amount of Emergy, the infrastructure in Macao was insufficient to extract it through proper waste disposal channels. (Zhou et al., 2011) studied MSW in South Beijing and analyzed processes including transport, mechanical separation, compost, incineration and landfill. They discovered composting and incineration to be better waste management options than landfilling and concluded that integrated treatment increased the Emergy of the MSW management system. (Liu et al., 2013) evaluated different waste treatment technologies in Liaoning province, China on the basis of their Emergy and concluded that landfilling was a better option than incineration for solid waste management. Among the different incineration options available, fluidized bed incineration was the worst option when human health was the main criterion, while sanitary landfill was the best. Similarly, grate type incineration was the worst for preventing ecosystem losses but the best option for maximizing electricity yields. In another study (Liu et al., 2017) compared four garbage treatment systems in Beijing, including separate collection and transportation, sanitary landfills systems, fluidized bed incineration system and a composting system. After considering the impacts of emissions, the options ranked in descending order of total Emergy usages were incineration followed by sanitary landfills followed by composting. Emergy wise, landfilling resulted in the lowest amount of environmental impacts. (Winfrey and Tilley, 2016) analyzed two waste treatment systems in Oklahoma, USA (a constructed wetland and a water treatment plant) using an Emergy based Waste Treatment Sustainability Index (TSI) which took into account the Emergy contributed from the waste itself rather than including all the Emergy of a waste flow as input or output. TSI does so by including the renewable Emergy (called *ENVload*) used by the environment to reduce the residual constituent of most concern (that the process does not manage to treat) to background concentrations. However, the calculation of *ENVload* highly depends on local environmental conditions (carrying capacity) which are difficult to estimate. For a case study in Oklahoma (USA), the authors discovered the constructed wetland to be a slightly better waste treatment option compared to a modeled active water treatment facility.

Some researchers believe that since cities depend on imported resources for their survival, as such the designing of material and energy flows in an urban environment needs to be monitored across all supply chains to ensure their long term sustainability (Viglia et al., 2017). Emergy analysis is just one of the tools to study MSWM sustainability and there can be other relevant metrics and assessment methods such as the cost-benefit analysis (Weng and Fujiwara, 2011). The main advantage of using Emergy analysis is its ability to incorporate environmental and socioeconomic flows, such as currency and labor along a common scale (Vega-Azamar et al., 2013). The role of socioeconomic flows is considerably important given that even though municipal solid waste management (MSWM) is seen to be the concern of relevant local authorities only, in fact a large number of stakeholders bear responsibility for its implementation (Guerrero et al., 2013). Thus MSWM requires not only technological evaluations and solutions but also an exploration of socio-cultural choices that can limit and effectively manage waste generation and disposal in a city. This is important as an effective MSWM strategy can reduce health impacts resulting from poor waste disposal practices (Liu et al., 2013).

As mentioned earlier, most of the studies on subject topic are limited to developed or newly industrialized countries such as China and Brazil. To the best of the authors’ knowledge this is the first instance that such an analysis is being conducted for a South Asian country and as such fills an important gap in the existing literature.

# Material and Methods

In this paper we will use Emergy accounting procedures to aid the environmental assessment of solid waste management alternatives in Gujranwala city. Data for this study was primarily obtained from government reports and other secondary sources such as publications of the Pakistani Ministry of Environment (Environmental Protection Agency, 2005), Japan International Cooperation Agency (JICA) (Japan International Cooperation Agency, 2015), Gujranwala Waste Management Company (GWMC), the World Bank (Altaf and Deshazo, 1996), United Nations Environment Program (UNEP), journal articles (Ali et al., 2016a, c), etc. The bulk of the data for this study was extracted from a survey conducted by JICA between the years 2014 and 2015 to characterize municipal solid waste in Gujranwala (Japan International Cooperation Agency, 2015). GHG emissions were calculated using a spreadsheet tool developed by the Institute for Global Environment Strategies (IGES) of Japan for developing countries in the Asia-Pacific region (Nirmala Menikpura, 2013). The output of this tool includes direct as well as net GHG emissions. Here direct emissions refer to GHG emissions due to fossil energy consumption, waste degradation, combustion of waste fractions, etc. Net GHG emissions are the emissions caused by the activation of the waste management strategies, minus the emissions avoided by the activation of those strategies (based on the GHG avoidance/mitigation potential of the selected technologies). The tool also calculates indirect savings which reflect material and energy recovery from waste management activities resulting in emission reduction. Hence an integrated system can result in an overall net climate benefit even though some of the constituent technologies result in an impact. The calculations were carried out according to the guidelines of the Intergovernmental Panel on Climate Change (IPCC) (Eggleston H.S., 2006). The tool reports the data in the form of kg CO2 equivalent per tonne of waste (kCO2eq/t). To measure the impact of these emissions, the output was expressed in the form of Disability Adjusted Life Years (DALY) using the Eco-indicator-99 life cycle impact assessment (LCIA) method (Goedkoop and Spriensma, 1999). DALY measures the impact on human health by accounting for the number of years lost due to ill-health, disability or early death. According to (Liu et al., 2013) this loss of human life can then be translated in terms of loss of Emergy invested by nature as well as the human society to produce the individuals that are affected by the impacts, according to the rationale that developing the given expertise or work ability and societal organization takes resources and when an individual is lost, new resources must be invested for replacement. Under this rationale, the DALYs can be used to convert the emissions into solar Emergy using appropriate unit Emergy values (UEVs) (Liu et al., 2013).

In this study we will provide different Emergy-based indicators, which are summarized in Table 1.

Table 1. Emergy-based indicators used in the study.

|  |  |  |  |
| --- | --- | --- | --- |
| **Indicator** | **Source** | **Use** | **Equation** |
| Emergy Yield Ratio (EYR) | (Brown and Ulgiati, 1997) | Used to measure the contribution of a scenario to the economy | EYR = (R+N+F)/F |
| Environmental Loading Ratio (ELR) | (Brown and Ulgiati, 1997) | Used to measure the stress on the environment arising from an individual scenario | ELR = (F+N)/R |
| Emergy Investment Ratio (EIR) | (Brown and Ulgiati, 1997) | Used to measures the investment made by the economy in exploiting local resources | EIR = F/(R+N) |
| Emergy Sustainability Index (ESI) | (Ohnishi et al., 2017). | Used to measure the contribution of a scenario to the economy per unit of environmental load | ESI = EYR/ELR |
| Emergy usage (U) | (Liu et al., 2013) | Used to measure the net Emergy resulting from the difference between Emergy investment into the system (Y) and Emergy loss due to the DALYs caused by the pollution generated by the technology (*Lw*) | U = R+F+N-*Lw* |

Here, R refers to Emergy input from renewable sources, F refers to imported Emergy input (both materials and services purchased from outside of the system) from the human economy, N refers to Emergy input from local non-renewable sources from nature, Y(=R+N+F) refers to the Emergy associated to the process output (Arbault et al., 2013), and *Lw* (defined in Eq. 1) refers to the Emergy loss due to the DALYs caused by the pollution generated by the technology.

# Results

# 4.1 Mass flow of waste in the city

Gujranwala city generated around 1200 tonnes/day of MSW in 2014 of which 1139 tonnes came from domestic households (Japan International Cooperation Agency, 2015) and the remaining waste came from other sources such as shops, restaurants, schools, streets, etc. Figure 2 illustrates the mass flow of urban solid waste fractions in the city. It can be seen that a large portion of the waste remained uncollected and most of the portion that was recycled was collected by the informal sector consisting of scavengers and private recyclers operating without any environmental or public health safety controls (Umair et al., 2015). This points towards the need for a significant improvement in solid waste collection and disposal system in the city. Currently, urban solid waste is dumped in open grounds on the outskirts of the city without any safety mechanisms. Two such dumping grounds are in use with waste storage volume of 510,000 m3 and 1.6 million m3 respectively and their combined waste storage capacity will be exhausted by 2018. Consequently, a third dumping ground having a capacity of 50 hectares has been proposed to be purchased, however, according to estimates, the city’s waste generation would reach 3346 tonnes/day in 2030 and this ground will also run out of space within the next 10 years (Japan International Cooperation Agency, 2015). Thus the city needs better waste management solutions to conserve precious urban real estate and to reduce the environmental impact of its waste.



**Figure 2.** Material flow diagram of municipal solid waste in Gujranwala city. Source - (Japan International Cooperation Agency, 2015)

# 4.2 Emergy flows

For this study we considered only household waste fraction as it was the largest component of the total municipal waste in the city and detailed information about its different fractions was readily available (Japan International Cooperation Agency, 2015). Three scenarios were considered for analysis which are given as follows:

* Scenario A - Involved the current practice in which all the domestic waste is landfilled/dumped without any pre-treatment or energy recovery.
* Scenario B - involved waste sorting for material recovery and composting followed by disposal of the remaining untreated waste in a sanitary landfill.
* Scenario C - Waste incineration in a stoker type incinerator with grates.

We did not consider other options such as anaerobic digestion, mechanical biological treatment or energy recovery options keeping in mind the local economic and technical assets, which impede the implementation of some of these disposal activities in Gujranwala city at the moment, due to lack of financial resources and skilled manpower. Energy recovery options from incineration and landfilling were also not considered in this analysis due to the unavailability of site specific data. Figure 3 shows the system boundaries for the integrated MSWM in Gujranwala city in the form of an Emergy system diagram.



**Figure 3.** Emergy system diagram of the integrated MSWM in Gujranwala city. HSW refers to household solid waste and C&T stands for collection and transportation.

Gujranwala city did not have an incinerator, composting plant or material recovery facility. However, we modeled the environmental impact of such provisions assuming that such systems had been installed and were actively operating in the city. In our model, scenario B included a semi-continuous stoker type incinerator which could reduce the waste to 75% by mass and 90% by volume without energy recovery. Since the whole country did not have any municipal waste incinerator, the utilities' requirements for incineration were determined using data from a medical waste incinerator at a public hospital in the nearby city of Lahore. This incinerator was consistent with the above mentioned assumptions of the incinerator used in the model. The average electricity and natural gas consumption for waste incineration came out as 1 kWh/67 kg waste and 3.36 liter/kg waste, respectively. For all scenarios average monthly fuel consumption for transportation was considered to be 1800 liters which reflects the currently reported fuel consumption for waste collection and transportation by GWMC (Japan International Cooperation Agency, 2015). Waste fractions reported in Table 2 were used as inputs for the three scenarios.

Table 2. Household solid waste by category.

|  |  |  |
| --- | --- | --- |
| **Components** | **Composition of wet fractions (%)** | **Quantity per tonne of waste (kg)** |
| Kitchen | 58.82% | 588.17 |
| Paper (Recyclable) | 3.29% | 32.86 |
| Paper (Other) | 4.60% | 45.95 |
| Paper (Total) | 7.88% | 78.82 |
| Textile | 4.92% | 49.19 |
| Grass & Wood | 2.58% | 25.81 |
| Plastic (Recyclable) | 1.20% | 11.99 |
| Plastic (Other) | 8.26% | 82.64 |
| Plastic (Total) | 9.46% | 94.63 |
| Leather & Rubber | 0.88% | 8.78 |
| Metal (Recyclable) | 0.13% | 1.29 |
| Glass (Recyclable) | 0.69% | 6.94 |
| Glass (Other) | 0.65% | 6.51 |
| Glass (Total) | 1.34% | 13.44 |
| Others | 13.99% | 139.88 |
| **Total** | **100%** | **1000** |

For scenario A, the input waste quantities consisted of all the waste fractions shown in Table 2. For scenario B composting fraction consisted of the kitchen waste and grass and wood waste. Recyclables shown in parenthesis in the table were assumed to be recovered. All the remaining fractions were considered to be landfilled. For scenario C composting and material recycling fractions were the same as those in scenario B. Incinerated waste consisted of all the remaining fractions. Table 3, 4 and 5 show the results of the calculations for each of the three scenarios. A complete breakdown of the calculations used to estimate the UEVs has been provided in the Appendix. All the UEVs presented in tables 3-5 have been taken from the cited references and updated according to the new global Emergy baseline (Brown et al., 2016). Please note that the value for waste collection services have not been provided owing to lack of data regarding all vehicles’ and containers’ current market value. Similarly, data for materials used in the construction of material recycling, composting and incineration facilities was unavailable. Also the Emergy values for labor in composting and incineration were included in their costs and could not be represented separately and hence emergy of labor in all three tables only represents those pertaining to waste collection only and as such they are the same. Please note that in the tables 3-5, Natural gas is the only local nonrenewable source of Emergy whereas water has been considered as a renewable source as Gujranwala lies between the two rivers of Ravi and Chenab and most of its water consumption comes from these rivers and their tributary canals.

Table 3. Scenario A (Landfilling).

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Source** |  | **units** | **Flows in units/tonne-of-waste** | **UEV (sej/unit)** | **References** | **Emergy (sej/tonne-of-waste)** |
| **Inputs** |  |  |  |  |  |  |
| Labor (F) |  | hr | 4.59E+00 | 3.09E+12 | Appendix | 1.42E+13 |
| Vehicles (F) |  | kg | 1.39E+03 | 8.58E+12 | (Agostinho, Almeida, 2013) | 1.19E+16 |
| Containers (F) |  | kg | 3.55E+02 | 8.58E+12 | (Agostinho, Almeida, 2013) | 3.04E+15 |
| Diesel (F) |  | J | 1.19E+08 | 1.37E+05 | (Agostinho, Almeida, 2013) | 1.63E+13 |
| **Outputs (Y)** |  |  |  |  |  |  |
| Landfilled waste | | kg | 1.00E+03 | 9.04E+11 | Appendix | 9.04E+14 |

Table 4. Scenario B (Composting, material recovery and landfilling).

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Source** | **units** | **Flows**  **in units/tonne**  **of waste** | **UEV (sej/unit)** | **References** | **Emergy**  **(sej/**  **tonne-of-waste)** |
| **Inputs** |  |  |  |  |  |
| COLLECTION | |  |  |  |  |
| Labor (F) | hr | 4.59E+00 | 3.09E+12 | Appendix | 1.42E+13 |
| Vehicles (F) | kg | 1.39E+03 | 8.58E+12 | (Agostinho, Almeida, 2013) | 1.19E+16 |
| Containers (F) | kg | 3.52E+02 | 8.57E+12 | (Agostinho, Almeida, 2013) | 3.02E+15 |
| Diesel (F) | J | 5.25E+06 | 1.37E+05 | (Agostinho, Almeida, 2013) | 7.22E+11 |
| COMPOSTING | |  |  |  |  |
| Compost production (F) | USD | 7.36E-01 | 3.54E+12 | Appendix | 2.60E+12 |
| Sorting cost organic (F) | USD | 0.00E+00 | 3.54E+12 | Appendix | 0.00E+00 |
| Water (R) | J | 3.45E+08 | 5.22E+04 | (Agostinho et al., 2013) | 1.80E+13 |
| SORTING |  |  |  |  |  |
| Sorting cost plastic (F) | USD | 3.60E+00 | 3.54E+12 | Appendix | 1.27E+13 |
| Sorting cost paper (F) | USD | 2.46E+00 | 3.54E+12 | Appendix | 8.73E+12 |
| Sorting cost steel (F) | USD | 2.58E-01 | 3.54E+12 | Appendix | 9.13E+11 |
| Sorting cost aluminum (F) | USD | 2.26E-01 | 3.54E+12 | Appendix | 7.99E+11 |
| Sorting cost glass (F) | USD | 5.55E-01 | 3.54E+12 | Appendix | 1.96E+12 |
| LANDFILLING | |  |  |  |  |
| Procurement (F) | USD | 9.58E-04 | 3.54E+12 | Appendix | 3.39E+09 |
| Engineering services (F) | USD | 6.27E-04 | 3.54E+12 | Appendix | 2.22E+09 |
| Construction (F) | USD | 6.37E-03 | 3.54E+12 | Appendix | 2.25E+10 |
| Machinery (F) | USD | 7.07E-04 | 3.54E+12 | Appendix | 2.50E+09 |
| Operations and Maintenance (F) | USD | 1.49E-03 | 3.54E+12 | Appendix | 5.27E+09 |
| **Outputs (Y)** |  |  |  |  |  |
| Compost | kg | 6.14E+02 | 1.61E+11 | (Agostinho, Almeida, 2013) | 9.91E+13 |
| Recovered Plastic | kg | 1.20E+01 | 7.45E+12 | (Agostinho, Almeida, 2013) | 8.93E+13 |
| Recovered Paper | kg | 3.29E+01 | 4.94E+12 | (Agostinho, Almeida, 2013) | 1.62E+14 |
| Recovered Aluminium | kg | 6.45E-01 | 1.59E+13 | (Agostinho, Almeida, 2013) | 1.03E+13 |
| Recovered Steel | kg | 6.45E-01 | 8.57E+12 | (Agostinho, Almeida, 2013) | 5.52E+12 |
| Recovered Glass | kg | 6.94E+00 | 2.75E+12 | (Agostinho, Almeida, 2013) | 1.91E+13 |
| Landfilled waste | kg | 3.33E+02 | 3.78E+11 | Appendix | 1.26E+14 |

Table 5. Scenario C (Composting, material recovery and incineration).

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Source** | **units** | **Flows in units/tonne of waste** | **UEV (sej/unit)** | **References** | **Emergy (sej/tonne- of-waste)** |
| **Inputs** |  |  |  |  |  |
| COLLECTION | |  |  |  |  |
| Labor (F) | hr | 4.59E+00 | 3.09E+12 | Appendix | 1.42E+13 |
| Vehicles (F) | kg | 1.39E+03 | 8.57E+12 | (Agostinho, Almeida, 2013) | 1.19E+16 |
| Containers (F) | kg | 3.52E+02 | 8.57E+12 | (Agostinho, Almeida, 2013) | 3.04E+15 |
| Diesel (F) | J | 5.25E+06 | 1.37E+05 | (Agostinho, Almeida, 2013) | 7.21E+11 |
| INCINERATION | |  |  |  |  |
| Electricity (F) | J | 5.40E+07 | 2.20E+05 | Appendix | 1.19E+13 |
| Natural gas (N) | J | 1.24E+08 | 3.67E+04 | (Odum et al., 2000) | 4.56E+12 |
| Incineration cost (F) | USD | 5.94E+02 | 3.54E+12 | Appendix | 2.10E+15 |
| COMPOSTING | |  |  |  |  |
| Compost plant expenses (F) | USD | 7.41E-01 | 3.54E+12 | Appendix | 2.62E+12 |
| Sorting cost organic (F) | USD | 0.00E+00 | 3.54E+12 | Appendix | 0.00E+00 |
| Water (R) | J | 3.45E+08 | 5.22E+04 | (Agostinho et al., 2013) | 1.80E+13 |
| SORTING |  |  |  |  |  |
| Sorting cost plastic (F) | USD | 3.60E+00 | 3.54E+12 | Appendix | 1.27E+13 |
| Sorting cost paper (F) | USD | 2.46E+00 | 3.54E+12 | Appendix | 8.71E+12 |
| Sorting cost steel (F) | USD | 2.58E-01 | 3.54E+12 | Appendix | 9.13E+11 |
| Sorting cost aluminum (F) | USD | 2.26E-01 | 3.54E+12 | Appendix | 8.00E+11 |
| Sorting cost glass (F) | USD | 5.55E-01 | 3.54E+12 | Appendix | 1.96E+12 |
| **Outputs (Y)** |  |  |  |  |  |
| Compost | kg | 6.14E+02 | 1.61E+11 | (Agostinho, Almeida, 2013) | 9.91E+13 |
| Recovered plastic | kg | 1.20E+01 | 7.45E+12 | (Agostinho, Almeida, 2013) | 8.93E+13 |
| Recovered paper | kg | 3.29E+01 | 4.94E+12 | (Agostinho, Almeida, 2013) | 1.62E+14 |
| Recovered aluminum | kg | 6.45E-01 | 1.59E+13 | (Agostinho, Almeida, 2013) | 1.03E+13 |
| Recovered steel | kg | 6.45E-01 | 8.57E+12 | (Agostinho, Almeida, 2013) | 5.52E+12 |
| Recovered glass | kg | 6.94E+00 | 2.75E+12 | (Agostinho, Almeida, 2013) | 1.91E+13 |

# 4.3 Emission impacts

In order to calculate GHG emissions from each of the scenarios we used the spreadsheet tool described in the Material and Methods section. These emissions were reported in kgCO2eq/t and were multiplied by the corresponding DALY and UEVs to yield the results in solar emjoules. Following (Liu et al., 2013) the equation used to perform the above mentioned calculation can be represented as follows:

(1)

Where *Lw* is the Emergy loss in support of human resources affected, *i* refers to the *i*-th pollutant, *m* is the mass of the chemicals released, DALY is the Eco-Indicator-99impact factor and *H* is the unit Emergy allocated to human resource per year, calculated as = total annual Emergy/population (Liu et al., 2013).

Table 6 shows the GHG emissions in kCO2eq/t as well as in solar emjoules. The human health impact per kg of CO2 emission, calculated as (2.10×10−7 DALYs/kg of CO2 emission) × (365 days/yr) × (1.22×1013 sej Emergy associated with Manpower (operator)/workday), is equal to 9.35E+08 sej/kg. Calculations for Emergy of Manpower (operator)/workday have been provided in the Appendix. It can be seen that the highest impact came from scenario A in which all the waste was landfilled. The lowest impact came from the Scenario C. Please note that negative results for net emissions indicate savings resulting from an integrated waste disposal system. Thus Net Emergy shown in Table 6 represents the Emergy of the system once the impact of emission savings has been accounted for. Without savings in emissions, Emergy losses due to human health impacts would be those represented by Direct Emergy loss in Table 6. In this study, Net Emergy serves to represent a potential reduction in human health impacts due to integrated waste management practices in Scenarios B and C.

Table 6. Emissions from the three scenarios (per tonnes of waste).

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Scenario | Direct emissions (k CO2eq /tonne) | Net emissions (kCO2eq/tonne) | DALY/Kg | Direct Emergy loss (sej/tonne) | Net Emergy (sej/tonne) |
| A | 704.97 | 704.97 | 2.10E-07 | 6.59E+11 | 6.59E+11 |
| B | 417.71 | -1415.28 | 2.10E-07 | 3.91E+11 | -1.32E+12 |
| C | 390.19 | -1692 | 2.10E-07 | 3.65E+11 | -1.58E+12 |

Figure 4 shows the results of the conversion in Emergy terms (using Eq. 1) of the impact of net emissions resulting from different waste disposal options for all three scenarios. It can be observed that landfilling results in the highest impact whereas composting results in the lowest impacts (i.e. highest avoided impacts) on human health.

**Figure 4.** Net values (per tonne of treated waste) of human health impacts of CO2 emissions converted in Emergy for the analysed scenarios

The results shown above point towards the need for development of proper waste disposal facilities in Gujranwala city. This can reduce the environmental footprint of the city’s waste and lead to resource conservation and pollution prevention.

# Discussion

Based on the above results one can compare the three scenarios in terms of their Emergy footprint. From Table 7 it can be observed that excluding the Emergy of untreated waste, the total Emergy usage of the three systems observes the following ranking: scenario C (1.72E+16 sej/tonne-of-waste) > scenario B (1.50E+16 sej/tonne-of-waste) = scenario A (1.50E+16 sej/tonne-of-waste). After considering the impact of net emissions the order of the Emergy usage (U) remains the same. Table 7 also provides the values of the different Emergy indicators calculated for each scenario.

Table 7. Values of the Emergy-based indicators for the three waste disposal scenarios.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Category | Unit | Scenario A | Scenario B | Scenario C |
| R | sej/tonne-of-waste | 0.00 | 1.80E+13 | 1.80E+13 |
| F | sej/tonne-of-waste | 1.50E+16 | 1.50E+16 | 1.71E+16 |
| N | sej/tonne-of-waste | 0.00 | 0.00 | 4.56E+12 |
| Y | sej/tonne-of-waste | 0.00 | 5.12E+14 | 3.86E+14 |
| *Lw* | sej/tonne-of-waste | 6.59E+11 | -1.32E+12 | -1.58E+12 |
| U | sej/tonne-of-waste | 1.50E+16 | 1.51E+16 | 1.72E+16 |
| EYR | dimensionless | - | 1.00 | 1.00 |
| ELR | dimensionless | - | 8.43E+02 | 7.65E+02 |
| EIR | dimensionless | - | 8.43E+02 | 9.61E+02 |
| %R | % | - | 0.11 | 0.10 |
| ESI | dimensionless | - | 0.001 | 0.001 |

These results suggest that scenarios A and B require almost the same amount of input Emergy, however if one considers the economic benefits of recovered materials and compost, social benefits of sanitary landfilling over incineration and open dumping (Dijkgraaf and Vollebergh, 2004) and the possibility of additional financial benefits through the sale of carbon credits, then Scenario B seems the most attractive option of the three scenarios which is also corroborated by EYR for the three scenarios. From the same table it can be seen also that ELR for Scenario C is less than that for Scenario B which means that the latter results in a greater stress on the environment than the former. However, EIR for Scenario C is greater that for Scenario B thus pointing out that Scenario B is a more sustainable option. Low %R values show that sustainability of both scenarios B and C is low and needs significant improvement. Studies show that energy recovery options can recover a portion of hitherto unrecovered Emergy even though this would require employment of further environmental resources for the installation of such energy recovery infrastructure (Liu et al., 2017). Thus Emergy recovery options might help to improve the indicators given in Table 7.

As mentioned earlier, Pakistan is a resourced constrained country and as such it lacks the financial and technical capital required for such investments. Yet the present system can be improved through waste minimization and enforcement of relevant environmental regulations which in turn requires a bottoms up behavioral change in the society through means such as targeted educational campaigns leading to greater awareness. This requires efforts from the local opinion leaders and political office bearers as well as the bureaucracy and the academia. The local society needs to be made aware of their stakes in the establishment of proper waste management systems for a sustainable solution to this issue. This might also lead the local civil society to raise necessary funds for the material resources needed by a proper waste disposal system. This is especially true in a society where most of the educational and healthcare facilities (Kassim-Lakha and Bennett, 2013) are being operated by philanthropic and private institutions and the size of household charities is around Rupees 142 billion or USD 1.66 billion per annum (Jehangir Khan and Arif, 2016). Many of these philanthropic and social welfare institutions are being run by faith based organizations and religious NGOs (Iqbal and Siddiqui, 2008) whose organizational capabilities have been actively employed for relief and rescue operations during national disasters such as floods (Yasmeen, 2012). The established network and structure of such organizations and other similar institutions can also be used for waste management activities as there is a strong stress on physical cleanliness and hygiene in the Islamic tradition and similar campaigns have been used in other predominantly Islamic societies (Ismail and Yusuff, 2013), (Aoki, 2015). Moreover, waste reduction and recycling facilities can be used for carbon credits thus leading to economic as well as environmental and social benefits (Johari et al., 2012). Finally, there is a need to highlight the subject issue through scientific and journalistic outlets to stimulate further research and to attain due attention from the concerned authorities. The population of Gujranwala district is greater than that of major European cities such as Rome or Berlin and as such the environmental and epidemiological impact of poor waste management controls in the city can affect a significantly large population. Thus the establishment of proper evaluation, monitoring and assessment tools is necessary for the design and implementation of an optimal waste management strategy for the city and its inhabitants.

# Conclusions

In this paper we aimed to appraise the environmental footprint of municipal solid waste management in a major city of Pakistan. We showed that currently only a small fraction of the urban solid waste is collected and that it is disposed through open dumping which represents an environmentally irresponsible solution. The city lacks sanitary landfills, composting plants or formal recycling units, however recyclable items from the waste are sorted by the scavengers for sale in the informal market. The current situation is unsustainable due to the economic, environmental and epidemiological burdens associated with it. We analyzed two scenarios in addition to the business as usual one and we found out that an integrated system consisting of sanitary landfilling, composting and recycling would represent the best alternative in terms of Emergy investment. It is important to mention here that for the current study we did not consider energy recovery options; else the results could have been different. Similarly, an economic cost benefit analysis was also not considered due to the unavailability of site specific data.

We suggested the involvement of the local civil society to aid in the establishment of better waste management controls. This can take the form of donations to help remove some of the financial constraints and similarly awareness campaigns led by opinion leaders can bring to waste minimization which in turn can reduce the burden of solid waste management even further. In the future similar studies can be conducted across other rapidly expanding secondary cities across the country and the region. These studies can be used for evaluation and benchmarking that can lead to local, sustainable solutions.

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# Appendix

All calculations in the appendix are based on old global Emergy baselines including that of 1.58E+25 sej y-1 (Odum et al., 2000). Final tables given in the body manuscript have been adjusted according to the new global Emergy baseline of 1.2E+25 sej y-1 (Brown et al., 2016).

**Table A1. Untreated Waste/Landfilled waste for scenario A**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Component | Units | UEV  (sej/unit) | Quantity | sej |
| Kitchen | kg | 3.21E+12a | 5.88E+02 | 1.89E+15 |
| Wood | kg | 3.20E+04b | 2.58E+01 | 8.26E+05 |
| Plastic | kg | 9.83E+12b | 9.46E+01 | 9.30E+14 |
| Paper | kg | 6.52E+12b | 7.88E+01 | 5.14E+14 |
| Glass | kg | 3.64E+12b | 1.34E+01 | 4.88E+13 |
| Steel | kg | 1.13E+13b | 6.45E-01 | 7.29E+12 |
| Aluminum | kg | 2.09E+13b | 6.45E-01 | 1.35E+13 |
| Textiles | kg | 1.10E+13 b | 4.92E+01 | 5.41E+14 |
| Leather | kg | 2.23E+11b | 2.94E+01 | 6.56E+12 |
| Rubber | kg | 2.23E+11b | 2.94E+01 | 6.56E+12 |
| Mixed | g | 2.41E+08c | 8.99E+01 | 2.17E+10 |
| Total |  | 6.98E+13 | 1.00E+03 | 3.96E+15 |

aFrom Table A3; b(Lei et al., 2008); c(Nepal et al., 2013).

Total weight of the waste represents wet fractions. The amount of moisture in the waste was discovered to be 70.06%. Thus the total Emergy of the dry waste was (3.96E+15)\*0.294=1.19E+15 sej/tonne. As water density is 1.00E+6 g/m3 it implies that 706 kg of water = 0.706 m3. Since Gibbs free energy of water = 5.00 J/g (Agostinho et al., 2013), total energy for the water contained in 1 tonne of waste is 3.53E+6 J/tonne. Thus Emergy of total untreated waste = (1.19E+15)+(3.53E+6)\*(6.89E+04) =1.19E+15 sej, where 6.89E+04 seJ/J is the transformity of water (Agostinho et al., 2013). The UEV results into 1.19E+15 sej/tonne or 1.19E+12 sej/kg or 1.19E+9 sej/g of untreated waste.

**Table A2. Landfilled waste for scenario B**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Component | Unit | UEV (sej/unit) | Quantity | sej |
| Plastic | kg | 9.83E+12b | 8.26E+01 | 8.12E+14 |
| Paper | kg | 6.52E+12 b | 4.60E+01 | 3.00E+14 |
| Glass | kg | 3.63E+12 b | 6.51E+00 | 2.36E+13 |
| Textiles | kg | 1.10E+13 b | 4.92E+01 | 5.41E+14 |
| Mixed | gram | 2.84E+06 c | 1.49E+05 | 4.23E+11 |
| Total |  | 3.16E+13 | 3.33E+02 | 1.70E+15 |

b(Lei et al., 2008); c(Nepal et al., 2013).

Again, assuming 70.06% water content, total Emergy of the dry waste = (1.70E+15)\*0.294=4.99E+14 sej. As water density is 1.00E+6 g/m3 it implies that 235 kg of water = 0.235 m3. Since Gibbs free energy of water = 5.00 J/g, total energy for the water contained in 1 tonne of waste is 1.17E+6 J/tonne. Thus Emergy of total untreated waste = (4.99E+14)+(1.17E+6)\*(6.89E+04) =1.19E+15 sej (Agostinho et al., 2013). The UEV results into 4.99E+14 sej/tonne or 4.99E+11 sej/kg or 4.99E+8 sej/g of untreated waste.

**Table A3. Kitchen waste**

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Component | kg/capitad | Percentaged | kg | kcal/kg e | kcal | J | sej/unitb | sej |
| wheat | 7.67 | 46.29 | 272.29 | 4.50E+03 | 1.23E+06 | 5.13E+09 | 6.80E+04 | 3.49E+14 |
| rice | 0.97 | 5.85 | 34.44 | 3.70E+03 | 1.27E+05 | 5.33E+08 | 3.59E+04 | 1.91E+13 |
| beans/pulses | 0.37 | 2.23 | 13.14 | 8.00E+02 | 1.05E+04 | 4.40E+07 | 6.90E+05 | 3.03E+13 |
| vegetable oil | 0.74 | 4.47 | 26.27 | 5.50E+03 | 1.44E+05 | 6.05E+08 | 1.71E+06 | 1.03E+15 |
| tea | 0.07 | 0.44 | 2.59 | 3.90E+03 | 1.01E+04 | 4.23E+07 | 2.00E+05 | 8.46E+12 |
| butter | 0.02 | 0.15 | 0.88 | 5.00E+03 | 4.41E+03 | 1.85E+07 | 1.71E+06 | 3.16E+13 |
| mutton | 0.07 | 0.42 | 2.49 | 2.71E+03 | 6.73E+03 | 2.81E+07 | 3.27E+06 | 9.20E+13 |
| beef | 0.22 | 1.33 | 7.81 | 2.71E+03 | 2.11E+04 | 8.85E+07 | 6.80E+05 | 6.02E+13 |
| chicken | 0.29 | 1.75 | 10.30 | 2.18E+03 | 2.24E+04 | 9.37E+07 | 1.71E+06 | 1.60E+14 |
| fish | 0.05 | 0.30 | 1.78 | 1.00E+03 | 1.78E+03 | 7.43E+06 | 1.71E+06 | 1.27E+13 |
| fruit | 0.40 | 2.41 | 14.20 | 5.00E+02 | 7.10E+03 | 2.97E+07 | 5.30E+04 | 1.57E+12 |
| vegetables | 4.13 | 24.93 | 146.62 | 1.02E+03 | 1.50E+05 | 6.26E+08 | 2.70E+04 | 1.69E+13 |
| salt | 0.23 | 1.39 | 8.17 |  |  |  | 1.00E+09 | 8.17E+09 |
| sugar | 1.33 | 8.03 | 47.22 | 4.50E+03 | 2.12E+05 | 8.89E+08 | 8.50E+04 | 7.56E+13 |
| Total | 16.57 | 100.00% | 588.17 |  |  | 8.13E+09 |  | 1.89E+15 |

b(Lei et al., 2008), d(Statistics, 2013), eValues derived from (FAO)

**Table A4. Diesel**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Vehicle | kg/liter | liter/kg | liter/tonne | Total vehicles | Fractions | Fuel consumption |
| armroll truck | 417 | 0.002 | 2.39 | 26 | 0.24 | 0.57 |
| tractor trolley | 246 | 0.004 | 4.06 | 37 | 0.34 | 1.39 |
| mini dumper | 311 | 0.003 | 3.21 | 45 | 0.41 | 1.33 |
| Totals |  | 0.009 | 9.67 | 108 | 1.00 | 3.31 |

Average fuel consumption results into 3.31 liters of diesel per tonne of waste.

1 liter of high speed diesel (HSD) = 35.9\*106 Joules

3.31 liters of HSD = 1.19\*108 Joules

**Table A5. Waste collection and transportation vehicles**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Vehicles | Daily waste collection (tonnes/vehicle) | Weight of vehicle in tonnes | Vehicle weight/tonne waste | Total vehicles | Fractions | Average weight |
| Arm roll truck | 3.16 | 8 | 2.53 | 26 | 0.24 | 0.60 |
| Tractor trolley | 2.53 | 2.7 | 1.06 | 37 | 0.34 | 0.36 |
| Mini dumper | 0.5 | 0.5 | 1 | 45 | 0.41 | 0.41 |
| Total |  |  |  | 108 |  | 1.39 |

Average vehicle weight per tonne of collected waste was 1.39 tonnes.

**Table A6. Labor**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Vehicles | Crew per vehicle (people) | Total vehicles | Total crew (people) | Total hours | Total waste in tonnes | Time (hours) |
| Arm roll truck | 1 | 26 | 26 | 208 |  |  |
| Tractor trolley | 2.5 | 37 | 92.5 | 740 |  |  |
| Mini dumper | 2.6 | 45 | 117 | 936 |  |  |
| Totals |  | 108 | 235.5 | 1884 | 410 | 4.59 |

Average time spent per tonne of waste was 4.59 hours per waste collection crew.

**Table A7. Container**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Container’s volume (m3) | Weight carrying capacity (tonnes) | Empty container weight (kg) | Waste weight per kg container | No of containers | %age | Weighted avg. waste weight/ Kilo Container |
| 5 | 2.5 | 900 | 2.77 | 216 | 0.93 | 2.57 |
| 10 | 6 | 1400 | 4.28 | 15 | 0.06 | 0.25 |
| Total |  |  |  | 231 |  | 2.82 |

Based on the ratio given above, the weighted average waste carried by each kilo of container was 2.82. This implies that every 1 kg of waste was supported by 0.354 kg of steel container. Thus 1 tonne of waste was supported by 354.6 kg steel container.

**Table A8. Compost (Field data)**

Composting Plant (Build Own Operate Transfer – 25 years)

Total Expenses = 5.52E+06 USD (excluding land cost and waste collection cost)

Capital expenditure (CAPEX) = 3.11E+06 USD

Compost production = 66000 tonnes/annum

Current compost production for 25 years @ 66000 tonne/annum = 1.65E+06 tonnes (A1)

Estimated compost for 25 years @ 300,000 tonnes/annum = 7.50E+06 tonnes (A2)

Average compost production for 25 years = average value of (A1) and (A2) = 4.58E+06 tonnes

Average compost expense per tonne = 5.52E+06/4.58E+06 = 1.21 USD/tonne

Average compost expense per kg = 1.21E-03 USD/kg

Compost cost = average compost expense/kg\*kg/tonne waste for compost = 1.21E-03\*6.14E+02

= 7.41E-01 USD

**Table A9. Water (Field data)**

Water content per kg of composted waste = 1.12E+02 liters

Total water consumed for composted waste = 1.12E+05\*6.14E+02 = 6.9E+04 liters = 69.07 m3 (A3)

Gibbs free energy of water = 5.00 J/g (A4)

Water density = 1E+06 g/m3 (A5)

Total energy used = (A3) \* (A4) \* (A5) = 3.45E+08 J

**Table A10. Recovered Materials**

|  |  |  |  |
| --- | --- | --- | --- |
| Component | kg | USD/kgf | USD |
| Sorting cost plastic | 1.20E+01 | 0.3 | 3.60E+00 |
| Sorting cost paper | 3.29E+01 | 0.075 | 2.46E+00 |
| Sorting cost steel | 6.45E-01 | 0.4 | 2.58E-01 |
| Sorting cost aluminum | 6.45E-01 | 0.35 | 2.26E-01 |
| Sorting cost glass | 6.94E+00 | 0.08 | 5.55E-01 |

f(Ali et al., 2016a).

**Table A11. Sanitary Landfill**

The table shows NPV of landfill cost items in Pakistani Rupees for the years 2016 through 2030.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Years** | **2016** | **2017** | **2018** | **2019** | **2020** | **2021** | **2022** | **2023** | **2024** | **2025** | **2026** | **2027** | **2028** | **2029** | **2030** | **Total** |
| Avg. Waste (tonne/day) | 1.80E+02 | 1.48E+03 | 1.60E+03 | 1.69E+03 | 1.80E+03 | 1.91E+03 | 2.04E+03 | 2.17E+03 | 2.30E+03 | 2.45E+03 | 2.60E+03 | 2.77E+03 | 2.95E+03 | 3.14E+03 | 3.35E+03 |  |
| **Stage 1** | | | | | | | | | | | | | | | | |
| Procurement of landfill site | 1.50E+05 |  |  |  |  |  |  |  |  |  |  |  |  |  |  | **1.50E+05** |
| Engineering services | 4.98E+04 | 4.98E+04 |  |  |  |  |  |  |  |  |  |  |  |  |  | **9.97E+04** |
| Construction | 4.93E+05 | 5.04E+05 |  |  |  |  |  |  |  |  |  |  |  |  |  | **9.97E+05** |
| Machinery | 3.15E+04 | 3.89E+04 |  |  |  |  |  |  |  |  |  |  |  |  |  | **7.04E+04** |
| Operations and Maintenance | 1.89E+04 | 2.19E+04 | 3.16E+04 |  |  |  |  |  |  |  |  |  |  |  |  | **7.24E+04** |
| **Stage 2** | | | | | | | | | | | | | | | | |
| Operations and Maintenance |  |  |  | 3.28E+04 | 3.15E+04 | 3.26E+04 | 3.36E+04 | 9.46E+04 | 4.38E+04 |  |  |  |  |  |  | **2.69E+05** |
| Engineering services |  |  |  |  |  | 4.87E+04 | 4.87E+04 |  |  |  |  |  |  |  |  | **9.74E+04** |
| Construction |  |  |  |  |  | 4.93E+05 | 5.04E+05 |  |  |  |  |  |  |  |  | **9.97E+05** |
| Machinery |  |  |  |  |  |  |  | 8.75E+04 |  |  |  |  |  |  |  | **8.75E+04** |
| Procurement of additional land |  |  |  |  | 3.00E+05 |  |  |  |  |  |  |  |  |  |  | **3.00E+05** |
| **Stage 3** | | | | | | | | | | | | | | | | |
| Operations and Maintenance |  |  |  |  |  |  |  |  |  | 4.48E+04 | 4.58E+04 | 1.07E+05 | 5.04E+04 | 5.16E+04 | 5.87E+04 | **3.58E+05** |
| Engineering services |  |  |  |  |  |  |  |  |  | 4.87E+04 | 4.87E+04 |  |  |  |  | **9.74E+04** |
| Construction |  |  |  |  |  |  |  |  |  | 4.93E+05 | 5.04E+05 |  |  |  |  | **9.97E+05** |
| Machinery |  |  |  |  |  |  |  |  |  |  |  |  |  | 1.74E+05 |  | **1.74E+05** |
| **Total** | **7.43E+05** | **6.15E+05** | **3.16E+04** | **3.28E+04** | **3.32E+05** | **5.74E+05** | **5.86E+05** | **1.82E+05** | **4.38E+04** | **5.86E+05** | **5.99E+05** | **1.07E+05** | **5.04E+04** | **2.26E+05** | **5.87E+04** | **4.77E+06** |

Source - (Japan International Cooperation Agency, 2015).

Prevailing rate in 2015-16 was about 1USD: 104 Rupees. The major cost items are given in USD below.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Cost Item | Cost (Rupees) | Cost (USD) | Total waste (tonne) | USD/tonne |
| Procurement | 450,000 | 4.33E+03 | 1.18E+07 | 3.66E-04 |
| Engineering services | 294,496 | 2.83E+03 | 1.18E+07 | 2.39E-04 |
| Construction | 2,990,406 | 2.88E+04 | 1.18E+07 | 2.43E-03 |
| Machinery | 332,100 | 3.19E+03 | 1.18E+07 | 2.70E-04 |
| Operations and Maintenance | 699,137 | 6.72E+03 | 1.18E+07 | 5.68E-04 |

**Table A12. Incineration (Field data for medical waste incinerator)**

Incineration Plant (25 years’ life assumed)

Cost of plant = USD 0.28 million (A6)

Maintenance cost = 1,144.23 USD/month = 3, 43,269.23 USD for 25 year period (A7)

Labor cost = 1,105.76 USD/month = 331730.76 for 25 year period (A8)

Incinerated waste = 1.8 tonne/month

Ash produced = 0.6 tonne/month

Waste incinerated at flat rate for 25 years @ 1.8 tonne/month = 540 tonnes (A9)

Total incineration cost for 25 years = (A6) + (A7) + (A8) = 0.96E+06 USD (A10)

Average incineration expense per tonne of waste = (A10)/(A9) = 1784.18 USD

Average incineration expense per kg of waste = 1.78 USD

Incineration cost = average incineration expense per kg \* kg/tonne of incinerated waste = 1.78\*332.94 = 594.02 USD

**Table A13. Emergy/money ratio for Pakistan**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Year | 2008g | 2006h | 2004g | 2000g |
| Emergy Use (sej) | 1.2E+24 | 6.59E+23 | 1.8E+24 | 7.4E+23 |
| GDP (USD) | 1.7E+11 | 1.37E+11 | 9.80E+10 | 7.39E+10 |
| Emergy/money ratio (sej/USD) | 7.05E+12 | 4.79E+12 | 1.83E+13 | 1.00E+13 |

g(Sweeney et al., 2007), h(DeVincenzo King, 2006).

Based on the table, curve fitting yields Emergy/money ratio for 2015 to be 4.66E+12 sej/USD based on Emergy baseline of 1.58E+25 sej y-1.

**Table A14. Emergy of Manpower (operator)**

Minimum wage in Pakistan in 2015 = Rs. 13000

Rupee:USD Exchange rate in 2015 = 104.75:1.00

Following (Ortega, 2000):-

Emergy of annual wages = (Rs.13000/sej/year)\*(12 month/month)\*(1 USD/year)\*(4.66E+12 sej/USD/Rs.104.75) = 6.939E+15 per USD (A11)

Annual energy spent by worker (operator) = 3200 Kcal/day \* 365days/year \* 4186 J/Kcal

= 4.889E+9 J/year (A12)

Emergy of hard worker manpower (operator) = (A11)/(A12) = 1.44E+06 sej/J (A13)

Emergy of manpower (operator) = 3\*(A13) = 3\*1.442E+06 = 4.26E+06 sej/J (A14)

Emergy of manpower (operator) in days =4.26E+06sej/J\*3000Kcal/day\*4186J/Kcal

= 5.35E+13 sej/day (A15)

Total working days in a year = 250 (assumption) (A16)

Assuming 8 working hours per day (i.e. 1/3 of a day), Emergy of Manpower (operator)/day = [(250/365)/3]\*(A15)

= 1.22E+13 sej/day = 4.07E+12 sej/hr

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Figure captions

Figure 1. Geographical localization of Pakistan and Gujranwala city.

Figure 2. Material flow diagram of municipal solid waste in Gujranwala city.

Figure 3. Emergy system diagram of the integrated MSWM in Gujranwala city. HSW refers to household solid waste and C&T stands for collection and transportation.

Figure 4. Net values (per tonne of treated waste) of human health impacts of CO2 emissions converted in Emergy for the analyzed scenarios.

1. by Nature (*ndr*). [↑](#footnote-ref-1)