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Recyclables Valorisation as the Best Strategy for Achieving Landfill CO_2e Emissions Abatement from Domestic Waste: Game Theory

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Abstract: Various nations in the world have developed technologies and strategies for appropriate waste disposal, and to abate waste generation and greenhouse gasses. Alternatives like recovering materials can help, but they require reliable information to improve planning and management. This study quantifies the Carbon dioxide (CO_2) emissions produced by the lack of valorisation of materials in a Mexican city. Two waste characterisations in a lower-class neighbourhood were carried out. For the CO_2 emission estimation, two scenarios were considered. DEFRA emission factors for waste treatment processes were used. Waste generation was 0.64 kg/capita/day in the first study, and 0.50 kg/capita/day in the second. The CO_2eq emissions of collected waste in the neighbourhood were estimated at 1824 kg for 2013 (0.20 kg/capita/day) and 1636 kg for 2015 (0.19 kg/capita/day). The behaviour of solid waste management in the city can be explained by the "prisoner's dilemma" model, studied in game theory, which is ideally suited to analysing situations affected by multiple agents, but requires an accurate understanding of solid waste actors and social implications.

Keywords: CO_2 emissions; solid waste; waste characterisation; game theory

1. Introduction

The improper handling of solid waste (SW) causes problems for both human health and ecosystems. For this reason, world nations have been prompted to develop technologies and policies for appropriate waste treatment at the end of the waste life cycle, and to abate waste generation. In developed countries, strategies for recovering and recycling materials, retrieving the potential energy of organic waste, and implementation of eco-labels, among others, have dramatically reduced the amount of SW deposited in landfills. The situation is different in developing nations, where the realistic best scenario for solid waste treatment is the landfill.

Today, the motivation behind improving waste management systems is not only to contain waste in one location (i.e., landfills) in order to avoid pollution and improve public health, but also to enable the use of material resources sustainably [1]. The use of virgin material for the manufacture of goods causes more damage to the environment than the use of recycled materials. Hossain et al. [2] pointed out that about 12% of total greenhouse gas emissions and 15% of energy consumption can be eliminated from the cement industry in Hong Kong by using waste materials to replace virgin materials. Rahim y Abdul [3] found a value of 0.84 kg of Carbon dioxide (CO_2/kg) in recycled resins produced, which is lower than virgin plastic resins of 2 kg CO_2/kg. De Michelis et al. (2007) note that a recycled material requires less energy to process. As an example, the use of Cadmium (Cd) and recycled Nickel (Ni) requires 46% and 75% less primary energy respectively, compared to extraction and refining of virgin metal [4].

There are alternatives to recovering materials from the waste, but to determine their viability, it is necessary to have information about the waste's characteristics. Waste characterisation studies provide information on the generation and composition of SW. It can strengthen decision-making and improve the planning and management of waste in its use and final disposal. Authors [5] indicate that a complete analysis of the characteristics and composition of household waste represents an important instrument for both local governments and landfill managers/operators in setting and achieving targets for waste recycling and recovery.

Waste characterisation studies need to be carried out by municipalities or academics periodically, and cannot be generalised to other localities or seasons, because there are variations in eating habits, consumption patterns, population composition, the season of the year, and economic income, among others, that can generate differences in the composition and generation of waste [6,7]. For example, a study in Mexico [8] reported significant differences in the amount and type of waste generated by two rural communities in the same municipality, separated by a distance of 21 km.

Waste valorisation contributes towards GHG reduction. In developed countries, this strategy has crystallised, dramatically reducing the number of valuable materials deposited in landfills, and the energy required for processing. However, in developing countries, this strategy is not practical or easy to achieve. For example, on 22 April 2016, Mexico signed the Paris agreement under the United Nations Framework Convention on Climate Change. The challenge for any developing country is massive, although the contribution that each one should make has been determined individually. In the "Waste" category, Mexico has been set a goal of a 28% greenhouse gasses emission (GHG) reduction by 2030. However, reaching that target will not be easy, due to the country's complex and limited waste management. For instance, open dumps and controlled disposal sites still exist. The total waste collected by the majority of municipalities is deposited in the sanitary landfill cells, although state and federal laws prohibit this practice. Therefore, it is not possible to measure the dimension of the problem by quantifying valuable materials that could be used as raw materials for industrial processes. In Morelia, Mexico, similar to other cities in developing countries, waste management is limited to collection and disposal in a sanitary landfill. The entry of scavengers/waste pickers into the landfill to segregate or valorise the waste is forbidden.

Several reports support the recycling or even material recycling desirability of domestic waste [9,10], but GHG waste emissions figures from developing countries are sparse, mainly because emission factors have not been reported. However, an approximation using local data might be useful in aiming to understand the feasibility of current GHG reduction choices. Game theory is the study of strategic decision-making. One of the most studied models is the prisoner's dilemma, which illustrates a delicate balance between simplicity and accuracy, but it also needs both a conceptual understanding of the effects of the processes in the problem. Solid waste management in a developing country indeed requires the latter.

Given the above problems, it was decided to carry out a study whose purposes were the following: (a) analyse and quantify the flow of domestic solid waste generated in the city of Morelia, Michoacán, Mexico; (b) quantify the CO_2 emissions produced by the lack of valorisation of materials; and (c) analyse the waste management and GHG reduction options considering the prisoner's dilemma. With these objectives, the information generated can be used to increase the awareness in the society and create a community-based integrated solid waste management.

2. Materials and Methods

Two similar studies were carried out, the first one in March 2013 and the second one in July–August 2015. Each study was conducted during six consecutive days in its respective period.

2.1. Area of Study

The city where the study was developed was Morelia, Mexico, located at 19°46′06″ N 101°11′22″ O. The average monthly minimum and maximum temperatures for March are 9 and 25 °C, respectively; 13 and 24 °C for July–August. In Mexico, the population is classified into six groups according to income from lowest to highest: E, D, D+, C, C+, B/A [11,12]. A lower-class neighbourhood (low/high or D+) was selected for this study. This is of interest to the government, because 32.6% of Mexico's population [12] belong to this class. This community is a private one, with 412 inhabited houses, with an average of three persons per dwelling. This neighbourhood represents typical social housing in Mexico, with a constructed area ≤65 m^2 including a bathroom, kitchenette, living room and two bedrooms [13]. In these households, the average monthly income is MXN $10,103.00 or USD $547 [14].

2.2. Domestic Solid Waste Characterisation

Some reports have pointed out that representative samplings of household solid waste (HSW) could be a truckload coming to waste transfer stations in a typical weekday collection [15], or a mixed sampling taken from a waste incinerator [16], among others. In this study, a waste collection truck (3.5 tonne payload capacity) was asked to start the collection trip in this neighbourhood, and to deliver the truck to the university once the service was completed for the studied area. The total waste collected was obtained by the difference obtained by the weight of the waste-loaded truck (gross weight) minus the weight of truck after discarding the waste (tare).

The coning and quartering method set out in the Mexican Standard NMX-AA-015-1985 [17] was used for waste characterisation, considering the waste delivered by collection truck. A uniform pile of solid waste is formed on the floor, or a flat horizontal area. The pile is mixed with a shovel and/or pitchfork until homogenised, then divided into four quarters using straight lines perpendicular to each other. These parts are named A, B, C, and D, following a clockwise direction. Then, either pair of opposite parts A and C or B and D are removed, repeating this operation until leaving a minimum of 50 kg of solid waste with which to make the selection of waste fractions.

The coning and quartering technique was operated until a final sample greater than 100 kg was obtained to ensure a representative sample. The standard indicates that a minimum of 50 kg of solid waste must be employed for the waste composition analysis. However, some authors [18,19] maintain that the optimum size of the sample ranges from 91 kg to 136 kg. Taboada et al. [8] point out that the measurements made in a 90 kg sampling do not change significantly from the ones made in samplings of up to 770 kg, taken from the same waste load.

The obtained sample was hand-sorted according to the Mexican Standard NMX-AA-022-1985 [20]. Some categories were used to complete the waste fractions found in characterisation. Afterwards, a new classification (recyclables) was performed with fractions that have the possibility of being marketable, in order to define the recovery potential of the waste. Each fraction was placed into individual plastic containers and were weighed afterwards. The portable electronic weighing scale used for waste quantification was an Uline H-670 with a 150 kg capacity and 10 g readability.

2.3. Waste Statistical Analysis

A hypothesis test of the difference between the two proportions was conducted to establish if there were any differences in HSW generation between the first study in 2013 (p_1) and the second in 2015 (p_2). Where components showed differences, a new hypothesis test was done to identify in which year more waste was generated, considering the following as an alternative hypothesis "More waste was generated in 2013 than in 2015 (Ha: $p_1 > p_2$)". Only components that could be recycled in the region were included in the ratio test. The MINITAB™ 16 statistical software with a 95% confidence interval was used for comparisons. The p-values used for the hypothesis test were obtained using the Exact Fisher test.

The p-value, CI's and Z_0-value from the hypothesis test of the difference between two proportions were calculated. With the p-value, the value of the test should be inferior to the significance level selected ($\alpha = 0.05$) in order to indicate a significant difference. With the CI, authors [21,22] pointed out that: (a) if the interval intersects zero, it is possible to conclude that the data is consistent with the null hypothesis, H0: $p_1 = p_2$; (b) if both of the CIs are positive, this indicates that the first ratio is greater than the second ratio; and (c) if both of the CIs are negative, then the second ratio is greater than first one. For the Z-values, when the alternative hypothesis is $p_1 > p_2$, the critical region is $z > 1.645$.

2.4. CO_2 Equivalent Characterisation Factors

For the emission estimation, two scenarios were considered, with the first considering only the waste collected in this study. The second included the projected waste generated by the city, considering the per-capita waste generation and composition of this study, the characteristics of the population analysed (lower-class) and their number in each year. For 2013, 709,870 inhabitants were considered (estimated by interpolation), and 784,776 inhabitants for 2015 [23].

The equivalent carbon dioxide (CO_2e) was calculated using the table DEFRA 2011 for emission factors for waste treatment processes [24]. Each category or group of categories is multiplied by the emission factor that corresponds to a particular waste scenario (landfilling) [25].

2.5. Game Theory

The outcome of game theory models can help in the approval and application of an overall sustainable option, taking into account the various actors involved—municipalities, landfill site owners, household waste generators and even environmental constraints—in making the negotiation amongst them more efficient. However, game theory is rarely reported for waste management. Some identified reports are Soltani et al. [26], Sabbaghi et al. [27] and Karmperis et al. [28].

For waste management analysis, a game matrix was used. The methodology employed to build it was the one exposed by Barrón [29]. These steps are as follows: in a zero-sum game, whatever one player wins, the other loses, so if a_{ij} is the amount player I receives, then player II loses a_{ij}. Now we have a collection of numbers $\{a_{ij}\}$ $I = 1, \ldots, n$, $j = 1, \ldots, m$, and we can arrange these in the matrix. These numbers are called the payoffs to player I, and the matrix is called the payoff or game matrix (see Table 1). By agreement, we place the player I as the row player and the player II as the column player. We also agree that the numbers in the matrix represent the payoff to player I. In a zero sum game the payoffs to player II would be the negative of those in the matrix. Of course, if player I has some payoffs which are negative, then player II would have a positive payoff.

Table 1. Game matrix sample.

	Player II			
Player I	Strategy 1	Strategy 2	...	Strategy m
Strategy 1	a_{11}	a_{12}	...	a_{1m}
Strategy 2	a_{21}	a_{22}	...	a_{2m}
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
Strategy n	a_{n1}	a_{n1}	...	a_{nm}

3. Results and Discussion

It is important to note that the data generated in this study could have limitations in their use due to the specific characteristics of the city, the population analysed, as well as the type of sampling obtained (wet wastes) and the duration thereof.

3.1. Domestic Solid Waste Characterisation

The total weight of collected waste was 5824 kg in 2013, and 4347 kg in 2015. In 2013, 433 occupied housing units were registered, with 1299 inhabitants. The daily waste collection was 832 kg/day, which indicates a per-capita generation (PCG) of 0.64 kg/capita/day. In 2015, 412 occupied housing units were registered, with 1236 inhabitants. The daily waste collection was 621 kg/day, which indicates an average generation of 0.50 kg/capita/day.

PCG in Morelia is below the values reported in other studies for cities in countries such as Cyprus [7], Turkey [6] or Oman [30] whose MSW generation rates range from 0.97 to 1.29 kg. However, it is bigger than Ghana [31] or China [32]. The difference in waste generation could be related to Gross Domestic Product (GDP). Authors [33–35] have pointed out that an increase in income results in a household waste generation rate increase and a change in waste composition (see the difference in the GDP in Table 2).

Table 2. Waste PCG and GDP per capita (current US$).

Country Name	GPC kg $hab^{-1}day^{-1}$	2011	2012	2013	2014	2015
China [32]	0.28	$5634	$6338	$7078	$7684	$8069
Cyprus [7]	1.28	$32,234	$28,951	$27,908	$27,341	$23,075
Ghana [31]	0.51	$1587	$1642	$1827	$1442	$1370
Mexico	0.64	$9730	$9721	$10,199	$10,353	$9005
Oman [30]	0.97	$21,164	$21,632	$20,205	$19,130	$15,551
Turkey [6]	0.98	$10,539	$10,539	$10,801	$10,304	$9126

Source: International Monetary Fund, 2017 [36].

The waste fractions are shown in Table 3. The components with small quantities concerning the general DSW composition were categorised in one single component (Others). The percentages in wet weight and standard deviations (σ) of the samples of each fraction are shown.

Table 3. Percentages in wet weight and standard deviations (σ) of the samples.

Components	2013		2015	
	%	σ	%	σ
Ferrous material	0.02	0.02	0.18	0.36
Paper [1]	2.64	2.23	3.96	2.74
Hazardous	0.15	0.13	0.55	0.83
Tin can	1.86	1.57	0.61	0.45
Polypropylene (PP:5)	1.12	0.94	0.75	0.29
Wood	0.29	0.24	0.97	1.57
Aluminium	0.28	0.24	1.03	0.65
Glass	3.44	2.90	4.24	1.06
Polystyrene (PS:6)	1.27	1.07	1.28	0.52
Tetra Pak packaging	1.91	1.61	1.35	0.47
Polyethylene (PET-1)	2.67	2.25	1.90	0.63
Textile/Cloth rags	3.93	3.31	3.24	1.76
Yard trimmings	2.88	2.43	3.21	3.48
High density polyethylene (HDPE:2)	5.52	4.66	3.68	1.34
Others [2]	6.10	5.14	3.74	1.68
Low density polyethylene (LDPE:2)	3.50	2.95	4.41	0.99
Toilet paper	5.40	4.55	4.44	2.27
Cardboard	3.60	11.79	4.74	1.95
Disposable diapers/sanitary towels	13.98	3.03	7.77	2.52
Food waste	39.44	33.26	47.96	6.74

[1] This category includes newsprint, glossy or magazine paper, and waxed carton packaging. [2] Ash, stones, foam, leather, cotton, electrical material, coal, aluminium foil, faeces, butts, hair, feathers, shoes, latex, ceramic, fine residue, and straw.

Table 4 shows DSW composition from Morelia compared to the ones found in other studies worldwide. The percentages do not follow a particular pattern according to GDP. Food scrap in this study was comparable to the rates of countries with a lower GDP [37], and was smaller than countries with a higher GDP [6]. Authors [30,38] have found that waste composition varies according to the season of the year, the lifestyles of the generators, demography, and geographic zones, among others.

Table 4. Solid Waste Composition in developing countries.

Component	Cyprus [7]	Turkey [6]	Oman [30]	Ghana [31]	Nepal [37]	Morelia
Paper and Cardboard	10.00	10.14	25.20	5.00	6.00	3.96
Plastics	6.68	8.75	16.40	14.00	10.00	12.02
Metals	(a)	0.82	2.80	3.00	5.00	1.64
Textiles	(b)	(a)	5.20	2.00	1.00	3.24
Glass	5.33	4.60	8.00	3.00	7.00	4.24
Food Scraps	34.24	61.64	33.60	61.00	46.00	47.96
Yard trimmings	13.06	1.25	(b)	(b)	(c)	3.21
Others	30.14	12.79	8.80	12.00	25.00	23.73

(a) The classification used does not allow the quantity to be defined; (b) None reported; (c) Included in food scrap.

3.2. Statistical Analysis

The p-value, CIs and Z_0-value from the hypothesis test of the difference between two proportions are shown in Table 5. Only the polystyrene (PS:6) category does not indicate a significant difference between 2013 and 2015. Ferrous material, paper, wood, aluminium, glass, low-density polyethylene, and cardboard increased their proportion in the waste stream; while tin cans, polypropylene, polyethylene and high-density polyethylene have decreased. This situation could be a consequence of waste management. In this city, the landfill operation is realised by a concessionaire, and the municipality pays per metric ton. As a result, there are powerful interests in all the waste going directly to landfill. The municipality does not have recycling programs, and there is a constant conflict with scavengers.

Table 5. p-Values and CIs of the analysed fractions.

Analysed Fraction	Ha: $p_1 \neq p_2$		Ha: $p_1 > p_2$	
	p-Value	CI	p-Value	Z_0
Ferrous material	0.000	(−0.0017, −0.0014)	1.000	−28.03
Paper	0.000	(−0.0138, −0.0125)	1.000	−40.64
Tin can	0.000	(0.0121, 0.0129)	0.000	59.02
Polypropylene (PP:5)	0.000	(0.0034, 0.0041)	0.000	20.57
Wood	0.000	(−0.0070, −0.0065)	1.000	−48.74
Aluminium	0.000	(−0.0078, −0.0072)	1.000	−52.91
Glass	0.000	(−0.0086, −0.0072)	1.000	−22.55
Polystyrene (PS:6)	0.628	(−0.0005, 0.0003)	—	—
Polyethylene (PET-1)	0.000	(0.0072, 0.0082)	0.000	27.57
High density polyethylene (HDPE:2)	0.000	(0.0177, 0.0192)	0.000	47.08
Low density polyethylene (LDPE:2)	0.000	(−0.0097, −0.0083)	1.000	−25.37
Cardboard	0.000	(−0.0122, −0.0107)	1.000	−31.41

3.3. CO_2equivalent

The CO_2 emissions of collected waste in the neighbourhood were estimated at 1824 kg CO_2eq for 2013 (0.20 kg/capita/day) and 1636 kg for 2015 (0.19 kg/capita/day). Organic waste (food and drink) is the category that corresponds to 86% of the potential bulk emissions at the landfill site (see Table 6).

Table 6. Waste tons collected and potential CO_2e emissions for landfill scenario.

	Morelia 2013	**Morelia 2015**	**Morelia 2013**	**Morelia 2015**
Waste Type	**Metric Tons**	**Metric Tons**	**kg CO_2e**	**kg CO_2e**
Glass	0.2	0.2	5	5
Clothing	0.2	0.1	85	52
Organic: food and drink waste	2.3	2.0	1562	1418
Organic: garden waste	0.1	0.1	29	24
Metal: aluminium cans and foil (excl. forming)	0.01	0.04	0.3	0.9
Metal: scrap metal	0.001	0.007	0.0	0.1
Metal: steel cans	0.1	0.02	2	0.5
Plastics: HDPE (incl. forming)	0.3	0.1	11	5
Plastics: LDPE and LLDPE (incl. forming)	0.2	0.2	7	6
Plastics: PET (incl. forming)	0.1	0.08	5	3
Plastics: PP (incl. forming)	0.06	0.03	2	1
Plastics: PS (incl. forming)	0.07	0.05	2	2
Paper and board: board	0.2	0.2	66	65
Paper and board: paper	0.15	0.17	48	54
Total			1824	1636

Interestingly, the obtained results can be expressed as a typical "prisoner's dilemma", the oldest and most studied model in game theory [39]: Two thieves plan to rob an electronic store, at the entrance, both are caught by the police for trespassing. The cops suspect their intention but lack evidence and require a confession to charge them with the greatest crime. Separately, the police tell each robber the following: "We are currently charging you with trespassing, which implies a month jail sentence; I know you were planning on robbing, but I need your testimony. In exchange for your cooperation, I will dismiss your trespassing charge, and your partner will be charged to the fullest extent of the law: a twelve-month jail sentence. I'm offering your partner the same deal. If both of you confess, your individual confession is no longer as valuable, and your jail sentence will be eight months each". Suppose both individuals are self-interested and only care about minimising their jail time.

The dilemma in solid waste management in Morelia city is whether the players choose the valorisation of solid waste. Both players—the municipality or "Player I", and the local private landfill concessionaire or "Player II"—are facing a dilemma, where the valorisation of domestic waste depends on several distinct conditions. In Mexico, the federal government has set a 50% decrease target on greenhouse gasses (GHG) emissions for the year 2050 [40], both players are expected to aim for this. Thus, CO_2e savings is considered the payoff for both players.

Three scenarios are available for both players:

(1) The municipality, an acutely underfunded entity, realises that in the year 2015 the organic waste (food and drink waste) is the largest portion of the waste stream (Table 6), and that diverting it from the local landfill would potentially represent a reduction of 1.4 ton CO_2e, according to Table 6. Furthermore, if organic waste is separated from the domestic stream for valorisation, it would represent a 48% saving scenario on landfill tipping fees, but the same amount of loss for "Player II".

(2) On the other hand, when considering waste valorisation of recyclable materials such as plastics or aluminium, potential CO_2e savings would be 100 kg CO_2e, regardless of the player that recovers this waste stream with an economic incentive.

(3) Another option, the valorisation of landfill biogas for energy production, would require substantial funds from both players; yet in Mexico, biogas is seldom considered an option for electricity or energy valorisation mainly due to lack of investment funds. In the year 2012, only three out of 196 landfill sites nationwide produced electricity [41]; the rest of the sites vented biogas passively into the atmosphere, even though emission abatement is widely encouraged by the federal government. Thus, no waste valorisation whatsoever is the third option for both players.

Table 7 represents the game matrix; the first player's strategy options are shown in rows and the second player's strategy options are shown in columns. For each player, waste valorisation, as the most desirable outcome with the largest CO_2e potential saving, implies a loss for the other one, particularly in the organic waste diverting scenario. This situation is inherently unstable, because there is no incentive for either player to choose this scenario; it is assumed that both are only self-interested and have no interest in "helping" the other player. Hence, the next desirable outcome (inferior, but sustainable) is that both players opt for the valorisation of recyclable material. The amount of potential CO_2e emission savings, in this case, is only 100 kg for the studied amount of waste. This outcome perplexes a lot of people new to the field of game theory; however, if both parties are self-centred, this is indeed the best strategy. Strategically, the choices for the municipality are <organic valorisation, no organic valorisation>, then the <recyclable valorisation, recyclable valorisation>, then the <no organic valorisation, organic valorisation> and lastly <no valorisation, no valorisation>. The game matrix for the year 2013 is similar, and the solution would also point to the valorisation of recyclables.

Table 7. Game matrix to solve the dilemma of potential CO_2e emission savings from a landfill site receiving domestic waste (year 2015 in Morelia, México).

	No Waste Valorisation (Private Landfill)		**Waste Valorisation (Private Landfill)**	
No waste valorisation (municipality)	+1636,	+1636	+1418,	−1418
Waste valorisation (municipality)	−1418,	+1418	−100,	−100

In Table 7, negative numbers represent CO_2e emission savings. The numerical value of 1418 corresponds to potential CO_2e from the organic fraction, 100 is the sum of emissions from metals and plastics (except PS), and 1636 corresponds to the total potential emissions for all the produced household waste.

For this particular scenario only, the implications of these results are three-fold: (a) the gap of interests between the municipality and the private landfill constitute the cornerstone of this strategy, the integration of a third actor such as the community is therefore needed to disrupt this dynamic; (b) CO_2e savings of 100 kg when diverting 1.54 t of recyclable waste is only a fraction of the total GHG emissions due to the valorisation itself, from a life cycle analysis perspective; and (c) landfilling in Mexico is the most employed option for waste disposal, but a possible strategy for organic waste requires a study on its own, taking into account the sustainability of any proposal.

4. Conclusions

The main contribution of this work was to present how the disconnection of interests from both the municipality and the local landfill represents the opportunity for a modest but probably sustained CO_2e emission saving strategy. Household solid waste generation and characterisation from two separate years did not change significantly in terms of influencing the outcome of the aforementioned strategy. The lack of domestic solid waste valorisation, particularly the organic fraction, represented the largest potential of GHG emissions from landfilling. Thus, other scenarios of waste valorisation seeking an equilibrium strategy should be obtained, where two or more players have no incentive to deviate from their chosen strategy after considering an opponent's choice. While game theory is well suited to analysing situations in which the decisions of multiple agents affect each agent's payoff, an accurate understanding of solid waste actors and social implications is needed. In addition, tools such as life cycle assessment in waste management are needed to provide such scenarios.

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