Current and future environmental impact of household solid waste management scenarios for a region of Brazil: carbon dioxide and energy analysis

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ABSTRACT

In Brazil, the largest share (51.4%) of municipal solid waste is composed of organic matter; however, composting is rarely used as a treatment technology. In 2008, only 3.8% of Brazilian municipalities had access to composting plants and about 11.6% of municipalities destined the municipal solid waste to recycling plants. This is only 1.4% of waste generated. Recycling and composting are key programs for municipalities to reduce environmental impact. Therefore, this study aims to evaluate the environmental impact of inserting a recycling, composting and integrated program in a region of Sao Paulo State, Brazil through the Waste Reduction Model method simulation of greenhouse gases emission (carbon dioxide equivalent and carbon equivalent) and energy use. The results show that recycling and composting can minimize the emission of greenhouse gases, reducing carbon dioxide and carbon equivalents, and promote energy savings. The best result is the integration of these techniques, which can reduce 78.8% of carbon dioxide and carbon equivalents and save 490.9% in energy versus baseline scenario. This study supports municipalities creating scenarios as a tool for planning and decision making to reach targets proposed by solid waste policies.

1. Introduction

Solid waste management and planning is necessary for several industries (Ben-Awuah, 2015) and for municipalities as part of their infrastructures. This management requires financial planning, operation and maintenance (Alm, 2015). Solid waste has already been defined as a solid material with negative economic values. This makes the disposal cheaper than its use (Pichtel, 2005). Thus, it is understandable that waste has a positive value. It is important to all of society — industries, government, and all stakeholders. This importance can be analyzed through significant growth trends of studies on the theme "solid waste" worldwide (Yang et al., 2012) and in Brazil (Deus et al., 2015) as well as and also in the current

standards in several countries of the world. In Brazil, it is controlled with Law No. 12305 of August 2, 2010, regulated by Decree 7404 of December 23, 2010. Here, the National Policy on Solid Waste (NPSW) allowed new opportunities for business (Almeida Júnior et al., 2012) and lessons that improve services and enable environmentally friendly actions (Jabbour et al., 2014).

The main topics of NPSW involve good practices recommended by Massoud et al. (2003) such as: increased coverage of the collection service; closing of existing open dumps; introduction of sanitary landfills; system integration as recycling, composting and/ or incineration; introduction of service charges; private sector involvement; deliberate responsibilities evaluation of the various stakeholders including families and other users of services, local and national government authorities, NGOs, formal and informal enterprises as well as external agencies. This results in shared responsibility.

There are several techniques and tools that analyze solid waste management systems (Pires et al., 2011). One of them is the

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construction of scenarios that deal with complex and dynamic systems. In addition, being part of the planning process provides viable guidelines for decision-making. This technique uses ideas, structures and uncertainty to construct plausible scenarios and become test conditions for the business concepts and generate results (van der Heijden, 2002). This method deals with thinking through future decisions and policies and creates possible alternative organizational strategies in several contexts and organizations (Postma and Liebl, 2005) as well as strategic planning in waste management for municipalities (Spoerri et al., 2009). Thus, it was questioned what will be the environmental impact be within 15 years if a group of municipalities—most them size—adopt recycling, composting, or both versus continuing on the same trend? This question is important because it shows there are few studies involving small municipalities.

Therefore, this study aims to create, evaluate and compare the environmental impact of some scenarios including inserting a recycling, composting and integrated program in a region Sao Paulo State through a simulation of Greenhouse Gases (GHG) emission (MTCO$_2$E - metric tons of carbon dioxide equivalent, and MTCE - metric tons of carbon equivalent) and energy use (BTU).

2. Background

This chapter is divided in four steps: 1) solid waste trends: presenting generation and composition of current and future trend on solid waste for world and Brazil; 2) Treatment and final disposal of solid waste: the fate of solid waste from Brazilian municipalities if they are treated or disposed without treatment on soil; 3) Brazilian National Policy on Solid Waste: Brazilian policy approaches to treatment and disposal of solid waste and where it cross with Zero Waste program; 4) Scenario as a tool for planning and decision making: a tool for municipalities managers. The model used in this study offers strategic planning to reach targets of current policy.

2.1. Solid waste trends

Waste and populations are growing. In Beijing, the population grew from 14.2 million in 2002 to 19.6 million in 2010, and the amount of municipal solid waste generated increased from 3.21 million tons in 2002 to 6.35 million tons in 2010. The percentage of organic waste increased from 45.8% in 2002 to 67.0% in 2010 (Wang and Wang, 2013). In Brazil, the amount of collected waste increased from 149,094.30 (t/day) in 2000 to 183,481.50 (t/day) in 2008 (Ministério do Meio Ambiente, 2012).

Fig. 1 presents the evolution of waste generation in the past and projections for the future in the world and its regions. The first scenario (SSP1) is 90% of the 7 billion of the world population live in cities, and development goals are achieved with reduced consumption of fossil fuels and environmentally aware citizens. In the second scenario (SSP2), there is a population of 9.5 billion people and 80% urbanization (intermediate scenario). In SSP3 scenario, there are 13.5 billion people and 70% live in cities. There is extreme poverty and moderate wealth. Many countries have high rates of population growth such as in Africa and Asia (Hoornweg et al., 2013). In Latin America, for intermediate scenario, the trend is that waste generation will grow strongly until 2025, and then grow less until 2070 and then stabilizes.

In Brazil, the composition of municipal solid waste is presented in Fig. 2. It is similar to that observed in other developing countries such as Mexico with the greatest share of organic matter (Buenrostro and Bocco, 2003). Developed and richer countries have less organic matter and more recycled materials, as observed in Portugal (Magrinho et al., 2006) and Greece (Erkut et al., 2008). The largest share of Brazilian waste is composed of organic matter (51.4%) followed by materials that can be recycled (31.9%). These are composed of glass, plastics, paper, steel and aluminum (Massukado et al., 2013). Solid waste composition is 46% organic, 17% paper, 10% plastic, 5% glass, 4% metal and 18% other (Hoornweg and Bhada-Tata, 2012).

2.2. Treatment and final disposal of solid waste

Organic matter can be recovered by composting. This is low cost compared to other approaches including landfill disposal (Barreira et al., 2008). It also reduces emissions of greenhouse gas (GHG) (Vergara and Tchobanoglous, 2012). Friedrich and Trois (2016) comment if 71,793 tons of garden waste were sent to composting through turned windrows it will emit 13,282 tons of CO$_2$ equivalent, however, if the same amount is not treated, then the emissions can reach 93,187 tons of CO$_2$ equivalent.

Thus, composting is an environmentally appropriate type of treatment for organic waste, but Brazil does not use this treatment technology. In 2008, only 3.8% of the municipalities had composting plants (Table 1). In São Paulo, it was just 2.8%. Compared with 2000, there were an increase of around 35% of municipalities in 2008 with composting. However, the quantity of waste (Table 2) composted decreased around from 76% in 2000−2008. This means is 6364.50 (4.5%) to 1519.50 (0.8%) (Instituto de Pesquisa Econômica Aplicada, 2012). Low and middle-income countries have a higher percentage of organic matter in their solid waste (up to 88%) versus high-income countries (<56%); however these developed countries have a higher amount of organic waste destined to composting (Hoornweg and Bhada-Tata, 2012).
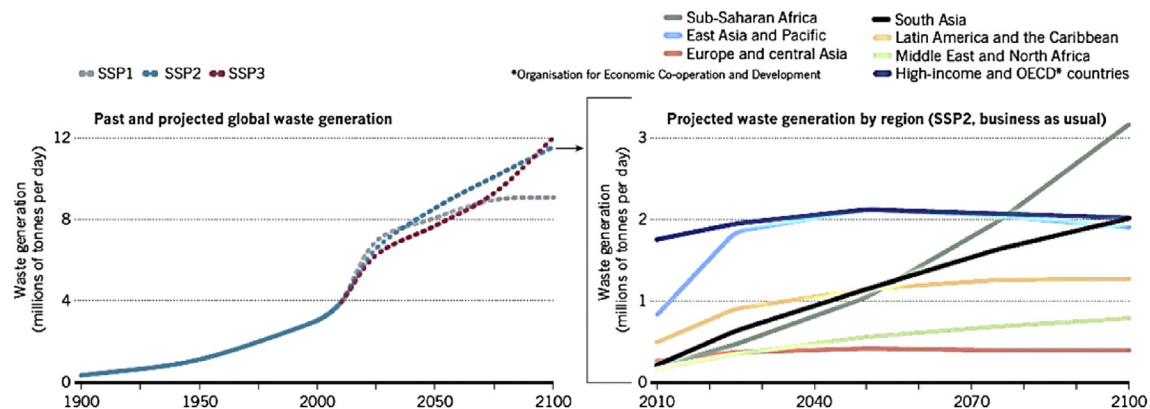

Fig. 1. Evolution of the generation of solid waste and its projections on three different scenarios. Source: Hoornweg et al. (2013).
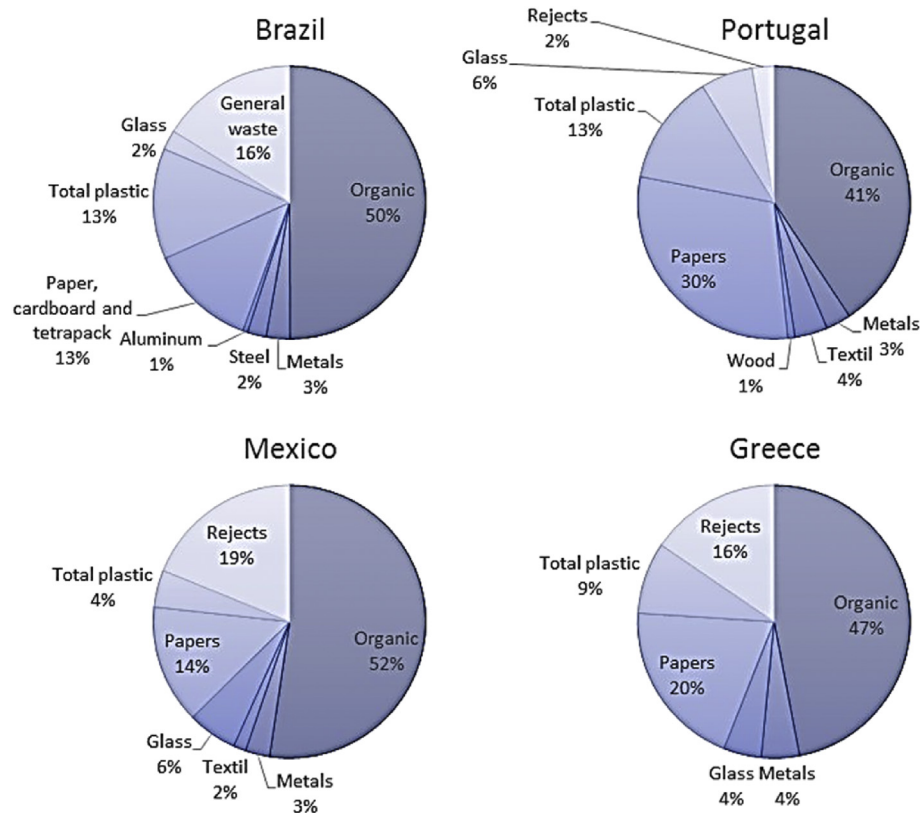
Fig. 2. Physical composition of municipal solid waste in Brazil, Portugal, Mexico and Greece. Source: Buenrostro and Bocco (2003); Erkut et al. (2008); Magrinho et al. (2006); Massukado et al. (2013).

Table 1
Disposal of municipal solid waste by number of municipalities.

Final destination	Number of municipalities		Percentage of municipalities	
	2000	2008	2000	2008
Sanitary landfill	810	1540	14.5	27.7
Controlled landfill	1074	1254	19.3	22.5
Open dumps	3763	2810	54.61	50.5
Composting plants	157	211	2.8	3.8
Recycling plants	248	643	4.5	11.6
Incineration plants	176	134	3.2	0.6
Dumping in wetlands	33	14	0.6	0.3
Not fixed places	109	—	2	—
Others	43	134	0.8	2.4
Total	5565	5565	—	—

Source: Instituto de Pesquisa Econômica Aplicada (2012).

Table 2
Daily amount of solid waste destined to different forms of final destination.

Final destination	2000		2008	
	Quantity (ton/day)	%	Quantity (ton/day)	%
Sanitary landfill	49,614.50	35.4	110,044.40	58.3
Controlled landfill	33,854.30	24.2	36,673.20	19.4
Open dumps	45,484.70	32.5	37,360.80	19.8
Composting plants	6364.50	4.5	1519.50	0.8
Recycling plants	2158.10	1.5	2592.00	1.4
Incineration plants	483.10	0.3	64.80	<0.1
Dumping in wetlands	228.10	0.2	35.00	<0.1
Not fixed places	877.30	0.6	—	—
Others	1015.10	0.7	525.20	0.3
Total	140,080.70	—	188,814.90	—

Source: Instituto de Pesquisa Econômica Aplicada (2012).

In Brazil, data suggests poor management of organic waste. The National Policy on Solid Waste in Brazil encourages treatment of waste before final disposal (Brasil, 2010).

The NPSW, Law 12.305/2010, in its Article 3, defines environmentally final disposal as the waste disposal that include reuse, recycling, composting, recovery and energy recovery or other destinations that avoid damage or risks to public health and safety and minimize adverse environmental impacts. Moreover, Article 36 shows that the holder of solid waste management can implement a composting system for organic solid waste and can articulate with stakeholders the ways of using compost (Brasil, 2010).

Recycling is an environmentally appropriate type of treatment for recyclable waste, but is rare in Brazil. It has a great potential for reducing GHG emissions and saving energy. Friedrich and Trois (2016) affirm that increasing the recycling rate of 10% can save 6,54,276 tons of CO_2 equivalent. Menikpura et al. (2013) studied the life cycle of municipal solid waste and declared that recycling can save 92% of total GHG. For Mahmoudkhani et al. (2014) recycling and composting scenario for a municipality solid waste management can significantly reduce GHG emissions and energy consumption.

In 2008, about 11.6% of the municipalities had recycling plants (Table 1). From 2000 to 2008, there was an increase of 157% in municipalities with solid waste recycling. However, the quantity of waste (Table 2) destined for recycling increased by 20% from 2000 to 2008. This means that 2158.10 (1.5%) to 2592.00 ton/day (1.4%). The total quantity of waste increased by 35%. It was 140,080.70 in 2000 and 188,814.90 ton/day in 2008 (Instituto de Pesquisa Econômica Aplicada, 2012). This result shows that recycling growth has not accompanied the general waste growth, so the share of amount destined to recycling decreased from 1.5% to 1.4%.

There are several factors that arrest the development and implementation of recycling programs such as government, educational, financial, administrative, and other factors (Troschinetz and Mihelcic, 2009). However, it is possible to implement successful programs that can achieve high levels of recycling as in Graz, Austria, where about 69% of household waste was recycled through a municipal program in 2004 and only 14% was disposed in a landfill (Moczygemba and Smaka-Kincl, 2007). There are others examples of programs that reach high levels of recycling and composting, Table 3 presents the amount of municipal waste generated and the percentage of treatment of some European countries.

2.3. Brazilian National Policy on Solid Waste

One of the goals of the National Policy on Solid Waste, Law 12.305/2010, in Brazil is the recycling and the encouraging of recycling industry. The law emphasizes the importance of recycling and encourages recycling to promote the use of raw materials and supplies derived from recyclable and recycled materials (Brasil, 2010).

The NPSW defines recycling as a process of transforming solid waste that involves its physical, physicochemical or biological changes or transforming it into new products (Brasil, 2010). This is the reason that recycling has great potential to reduce emissions of greenhouse gases, energy consumption and even water consumption due to the substitution of virgin materials, as observed by Fujii et al. (2014) on a recycling system for municipal solid waste. Mahmoudkhani et al. (2014) analyzed some scenarios with life cycle assessment, and Zaman (2014) measured performance of Zero Waste Index in a municipality.

It is important to highlight that NPSW has goal similar to Zero Waste program (Fig. 3), which is "designing and managing products and processes to systematically avoid and eliminate the volume and toxicity of waste and materials, conserve and recover all resources, and not burn or bury them" eliminating all disposal in soil (Zero Waste International Alliance, 2009).

2.4. Scenario as a tool for planning and decision making

Faced with a wide solid waste management tool, scenario building helps in the planning process to provide supports for decision-making (Pires et al., 2011). The scenarios technique is a prospective study that aims to describe alternative futures as a support in the decision and choice of the best alternative. Thus, this technique describes future possible or desirable situations as well as the entire process or path that connects to the initial situation (Buarque, 2003). Therefore the scenarios can contribute to real options on three main levels: 1) assist in the identification of future options; 2) help in decision time of implementing an option; 3) provide important information in the evaluation of real options (Cornelius et al., 2005).

Pollard and Hotho (2006) comment that the use of scenarios helps open new possibilities for strategic management analysis. This enables assessment of what could go wrong with following a strategy and a specific plan. Furthermore, the scenarios technique allows an approach for potential problem identification that can be treated with potential solutions.

Some authors divide the scenarios technique into two major groups: exploratory and desired or normative (Godet, 2000). The desired scenario reflects the best forecast, with reasonable and feasible description. This scenario is a plausible utopia that is has the best features and is technically and logically feasible. The desired scenario is the synthesis of the current reality. This is antithesis to the ideas and utopias of a society in relation to future (Buarque, 2003). This scenario builds alternative visions of desired future, but it also can build the most feared (Godet, 2000).

In scenarios development, Godet (2000) said that the main steps are: 1) identify the key variables of the objective of structural analysis; 2) analyze the games of stakeholders with important issues for the future, and 3) reduce uncertainties and choose the most probable scenarios. According to Börjeson et al. (2006), scenarios can also be divided according to use based on the following questions: What will happen? What can happen? and How will a specific target be achieved?

Some models for scenario building as a tool for planning and decision making are found in the literature including the Soil and Water Assessment Tool model used to quantify the impact of soil on land use (Boluwade and Madramootoo, 2015). The Life Cycle Assessment can evaluate complex systems including biogas generation (Rege et al., 2015) and solid waste management evaluation scenarios (Al-Salem et al., 2014). The Waste Reduction Model (WARM) created by the United States Environmental Protection Agency is one model widely used to determine the best options for reduction of greenhouse gas (GHG) emissions and energy consumption. Barros et al. (2013) used it to evaluate the impact of energy and the generation of greenhouse gases when implementing a selective collection program on a university campus. Brown (2016) emphasized that the WARM protocol focus on carbon emissions; Greene and Tonjes (2014) concluded that indicators like the WARM can provide important information for waste managers and policy makers to be helpful in performance and progress analysis. Lai et al. (2014) analyzed the environmental impact with WARM for the current and futures alternatives of a waste disposal program in the Region of Waterloo.

3. Materials and methods

This work addressed a normative/desired scenario of the type preservation for maximum environmental efficiency. The scenario consists of a set of plausible hypotheses that converge on the desires of society and government for the future. The process begins with the construction of a desired and ideal future hypothesis (Zero Waste) that will serve as a reference. A Zero Waste program

Table 3
Some European countries and their percentage of waste treatment in 2011.

Country	Municipal waste generated, kg per person	Total municipal waste treated, kg per person	Municipal waste treated, %			
			Landfilled	Incinerated	Recycled	Composted
Austria	552	528	3	35	28	34
Belgium	465	460	1	42	36	20
Germany	597	597	1	37	45	17
Luxembourg	687	687	15	38	27	20
Netherlands	596	502	1	38	32	28
Sweden	460	460	1	51	33	15

Source: Adapted from Eurostat Press Office (2013).

Fig. 3. Zero waste hierarchy according to the Zero Waste International Alliance. Source: Xevgenos et al. (2015).

provides an ideal development for municipalities on the issue of solid waste management even if there is a great difficulty to achieve their goals. This benefits from virgin materials substitution, energy savings, emissions saving and water savings (Zaman and Lehmann, 2013).

Understanding the concept of zero waste includes zero wastage, which means meaning a recycling rate of 100% and recovery of all resources from generated materials (Zaman and Lehmann, 2011). The ideal scenario was built from this starting with a target of 5%–100% in 15 years (52.5% total) (Fig. 4).

The environmental impact including air impact translated in GHG emission and energy use by inserting composting (Scenario C), recycling (Scenario R) and integrated (Scenario R + C) program over 15 years starting with 5% and reaching 35% in the final year (20% total) (Fig. 4) was questioned. The baseline scenario was compared to (current trends) the ideal scenario (Zero Waste program).

The municipalities studied here (Fig. 5) were selected because they share a private landfill in the city of Cachoeira Paulista. This having a composting and recycling plant in the same municipality would be more feasible. This scenario was used in the simulations.

Several models in the literature have determined the best options for reduction of greenhouse gas (GHG) emissions and energy consumption. In this study, the model was the Waste Reduction Model (WARM) version 12. The development of data of GHG emissions was according to the Life Cycle Assessment (LCA) using estimation techniques produced by GHG emission inventories (Environmental Protection Agency, 2006). The outputs are total $MTCO_2E$ (metric tons of carbon dioxide equivalent), total of MTCOE (metric tons of carbon equivalent) and Energy Use (millions of BTU).

The simulation of the environmental impact assessment used the gravimetric composition of municipal waste and the generation trend was presented in the Integrated Sanitation Plan of each municipality. Fig. 6 shows the general summary of this research method.

4. Results and discussion

The Integrated Regional Sanitation Plan of the region serves the municipalities of this study (Table 4). It highlights the important role of municipalities in the region in the form of cooperation and
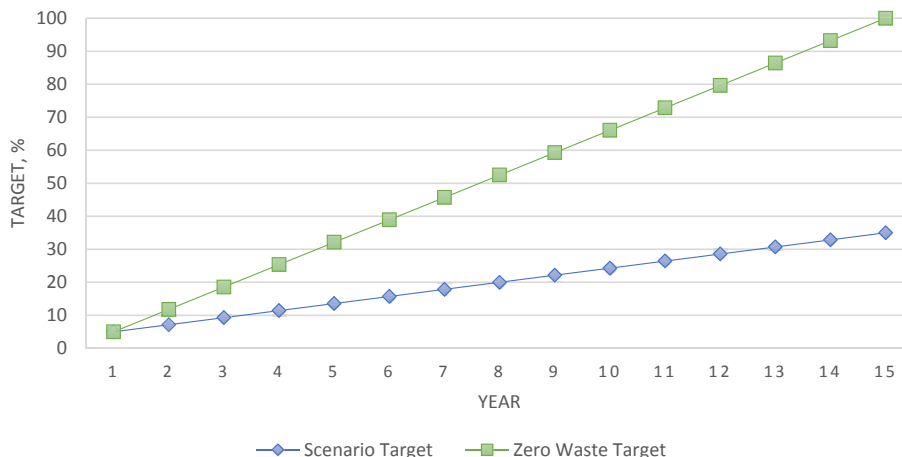

Fig. 4. Annual targets for the scenarios over 15 years.

Fig. 5. Map indicating the municipalities that use the landfill in Cachoeira Paulista/SP, Brazil.
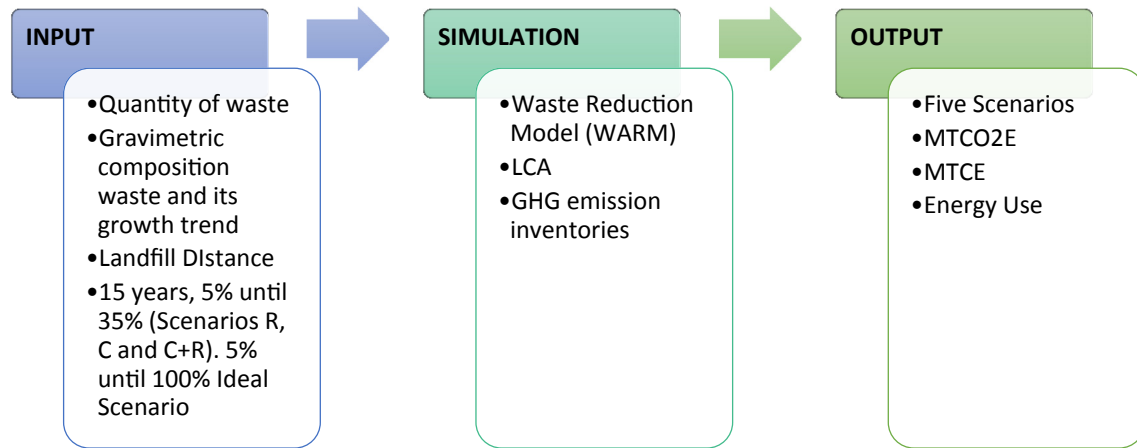

Fig. 6. General summary of the research method.

Table 4
Municipalities selected for study and their characteristics.

City	Population 2010	Waste production (t/day)	Has solid waste integrated management plan	Has integrated sanitation plan	Has recycling program*	Has composting program*	*VerdeAzul* city program score 2014 (rank)	Average distance from the landfill (km)
Aparecida	35,007	26	No	Yes	No	No	35.38 (389°)	39.7
Cachoeira Paulista	30,091	14.67	No	Yes	No	No	34.66 (391°)	4
Canas	4385	1.6	No	Yes	No	No	–	9.9
Cruzeiro	77,009	36	No	Yes	No	No	37.38 (371°)	20.1
Cunha	21,866	5.53	Yes	Yes	Yes	No	1.74 (586°)	83.4
Guaratinguetá	112,072	73.33	Yes	Yes	Yes	Yes	1.78 (585°)	35.6
Lavrinhas	6590	2	Yes	Yes	No	No	1.39 (589°)	26.9
Lorena	82,537	43.3	Yes	Yes	Yes	No	48.11 (318°)	15.8
Potim	19,397	9	No	Yes	No	No	–	42.8
Queluz	11,309	1.88	No	Yes	No	No	1.07 (593°)	46.2
Roseira	9599	5	Yes	Yes	Yes	No	19.19 (442°)	49.8
São José do Barreiro	4077	1.54	No	Yes	No	No	9.25 (548°)	75.2
Silveiras	5792	0.67	No	Yes	Yes	No	13.88 (466°)	28.4

Source: Adapted from CETESB (2016); IBGE (2010); * According to the Integrated Sanitation Plan.

partnerships for the construction of integrated regional solutions for solid waste management. It also creates regional units of waste sorting and composting in areas close to the cities of Cachoeira Paulista, Tremembé, São José dos Campos and Guararema. There is installation of regional landfills in Cachoeira Paulista, Tremembé and Santa Isabel and the implementation of an Energy Recovery

Unit to serve the Vale do Paraíba region (Secretaria do Meio Ambiente do Estado de São Paulo, 2014).

The municipalities involved are not certified in the *VerdeAzul* City program of State of São Paulo. They have low grades, and the higher of them is Lorena (48.11 points). This is far from the minimum of 80 points required for certificate municipalities. This program encourages and empowers local governments in the implementation and development of a strategic environmental agenda within 10 directives—one of them is solid waste (Secretaria do Meio Ambiente, 2014).

Characterization of the municipal region is presented in Table 5. There is waste collection in 99.33% of households, which is an important feature. However, Table 4, shows that of 13 municipalities, only 5 have some type of recycling program and only 1 has composting. While this is only tree pruning waste, it is the baseline for the 5% target for recycling and composting (Fig. 4) depending on the scenario (Fig. 7).

The 12 municipalities are small (<100,000 inhabitants), and this size often has more problems that are not addressed. They have less human, financial and technical resources at their disposal. These types of municipalities are often underserved in housing, transportation, piped water, waste disposal and other services (United Nations Population Fund, 2007).

The landfill is owned by the municipality of Cachoeira Paulista, which outsourced its operation to the private company VSA − Vale Soluções Ambientais Ltda. The license covers municipal solid waste IIA class (organic and non-inert), and their standard is quite satisfactory with scores of 9.4 for the Landfill Quality Index, which can reach up to 10 points (CETESB, 2013).

The construction of scenarios occurs after targets are achieved for global warming remediation. In 2009, Brazil was instituted the National Policy on Climate Change (NPCC) by Law No. 12.187/2009. The NPCC formalizes the voluntary commitment of Brazil to the UN Framework Convention on Climate Change about reduction of GHG emission between 36.1% and 38.9% of projected emissions by 2020 (Brasil, 2009). The Brazilian National Plan on Climate Change is based on this policy and outlines a goal of increasing the recycling of solid waste to 20% by the year 2015 (Brasil, 2008).

Based on the goals and the feasibility that already occurs in some countries (Table 3), four alternative scenarios were developed beyond the current trajectory (Fig. 7). These check the environmental impact, and this impact quantifies emissions of greenhouse gases.

As shown in the baseline scenario (Table 6 and Figs. 7–10) of municipalities throughout the 15 years were analyzed. This will emit 369,662.8 of $MTCO_2E$, 100,817.1 of MTCE and consume 531,086.8 of M BTU. Compared to the other scenarios, the current trend is the worst.

As for Scenario C (Table 6 and Figs. 7–10) involves the composting of organic materials, and there will be emission of 279,654.7 $MTCO_2E$ and 76,269.5 of MTCE. This represents a reduction compared to the baseline scenario of 24.3% for both. The energy consumption is 568,323.7 M BTU, which represents an increase compared to the baseline scenario of 7%. The biggest advantage of this scenario is the lowest emission $MTCO_2E$ and MTCE and the disadvantage of this scenario is the energy consumption. This is due to the fact that the production of compounds—particularly with better quality—requires energy (Lou and Nair, 2009). However, composting can have a better cost-benefit ratio in addition to moderate environmental impacts (Aye and Widjaya, 2006). In addition, Taheri et al. (2014) recommend composting together with landfill management. Of note, some are of low quality and require an efficient municipal program with proper separation and better use of technology to purify waste (Barreira et al., 2008).

Table 6 and Figs. 7–10 show that the recycling Scenario (R) of 20% of total recyclable waste is super in all aspects—especially in total energy. This is because recycling has great potential to reduce emissions of greenhouse gases, energy consumption and even water consumption due to the replacement of virgin raw materials, as confirmed by Friedrich and Trois (2016) study on municipal solid waste in a municipality of South Africa. Menikpura et al. (2013) also confirm in their study that recycling had so effective for GHG emissions reducing. This is supported by Zaman's (2014) Zero Waste research. Thus, in this scenario, there will be a total emission of 190,601.3 $MTCO_2E$ and 51,982.2 of MTCE. It will avoid consumption of 2,113,276.1 M BTU of energy, which is a huge change from the baseline. This is a reduction compared to the baseline scenario of 48.4%, 48.4% and 497.9%, respectively.

Lino et al. (2010) reported that the insertion of recyclable collection in Campinas city even if only 1% of the total can lead to energy savings of 3,486,722.2 kWh/month. This equals a monthly energy consumption of 4000 houses.

The Scenario R + C (Table 6 and Figs. 7–10) shows that recycling and composting offer lower emissions of $MTCO_2E$ and MTCE due the combined use of recycling and composting similar to Mahmoudkhani et al. (2014). Therefore, this scenario will emit 100,593.2 of $MTCO_2E$ and 27,434.5 of MTCE, and will avoid the use of 2,076,039.0 M BTU. This represents a difference of 72.8%, 72.8% and 490.9% versus baseline. The integration of recycling and composting will decrease greenhouse gas emissions considerably versus baseline. The total energy is negative. It is slightly less than Scenario R because energy is used in composting.

The Ideal Scenario (Table 6 and Figs. 7–10) using recycling and composting (100% at the end of 15 years) generates carbon credits. This credit is possible as occurred in Adelaide (Australia), San Francisco (USA) and Stockholm (Sweden) (Zaman and Lehmann, 2013). Therefore, this scenario avoids emission of 336,645.7 $MTCO_2E$ and 91,812.5 of MTCE. It will avoid energy use of
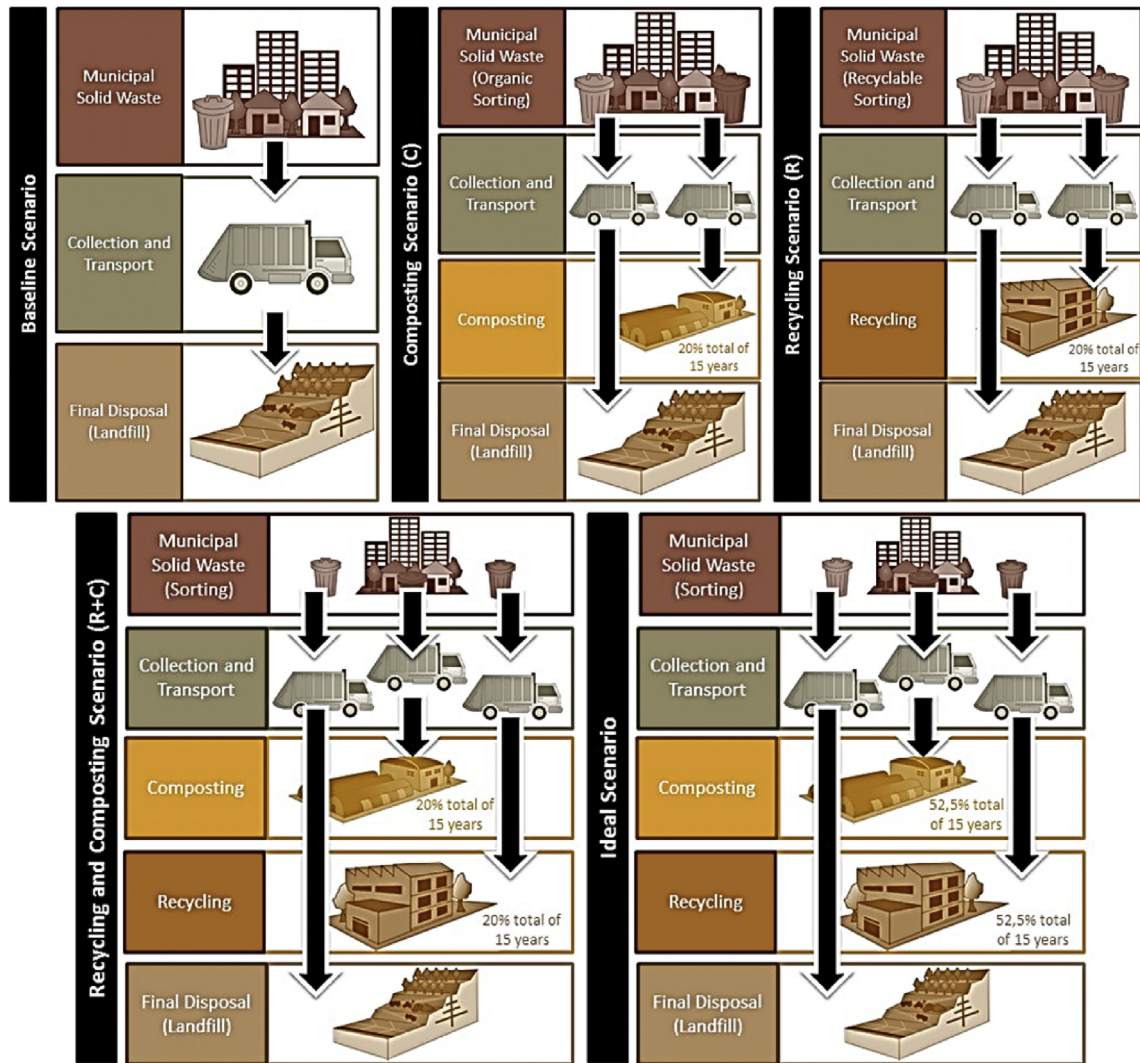
Table 5
Characterization of the municipal region.

Indicator	Characteristic
Preponderant use	Industrial
Municipalities (34)	Aparecida, Arapeí, Areias, Bananal, Caçapava, Cachoeira Paulista, Canas, Cruzeiro, Cunha, Guararema, Guaratinguetá, Igaratá, Jacareí, Jambeiro, Lagoinha, Lavrinhas, Lorena, Monteiro Lobato, Natividade da Serra, Paraibuna, Pindamonhangaba, Piquete, Potim, Queluz, Redenção da Serra, Roseira, Santa Branca, Santa Isabel, São José do Barreiro, São José dos Campos, São Luís do Paraitinga, Silveiras, Taubaté e Tremembé
Population	1,894,716 inhabitants (4.7% of state of São Paulo population)
Area	14,444 km²
Added Value	42 billion reais (42.82% from the services sector)
Average level of attendance by regular garbage collection	99.33% of urban permanent private households
Level of service for sewage system collection	88% of the population served by sewage collection service
Level of service for sewage treatment	59% of the population served by sewage treatment
Certificates municipalities by *VerdeAzul* City program in 2012	−
Municipality that presented to VerdeAzul City program the Solid Waste Integrated Management Plan in 2012	Lorena

Source: Adapted from Secretaria do Meio Ambiente do Estado de São Paulo (2014).

Fig. 7. Graphical schema of scenarios.

Table 6
Comparison of scenarios of Emission of greenhouse gases and energy use: total and percentage variation of alternative scenarios compared with baseline scenario (%).

	Baseline scenario	Scenario C	Scenario R	Scenario R + C	Ideal scenario
Total of MTCO$_2$E	369,662.8	279,654.7 (−24.3%)	190,601.3 (−48.4%)	100,593.2 (−72.8%)	−336,645.7 (−191.1%)
Total of energy (millions of BTU)	531,086.8	568,323.7 (7.0%)	−2,113,276.1 (−497.9%)	−2,076,039.0 (−490.9%)	−6,312,631.7 (−1288.6%)
Total of MTCE	100,817.1	76,269.5 (−24.3%)	51,982.2 (−48.4%)	27,434.5 (−72.8%)	−91,812.5 (−191.1%)

MTCO$_2$E: metric tons of carbon dioxide equivalent; MTCOE: metric tons of carbon equivalent.

6,312,631.7 M BTU. This represents a difference 191.1%, 191%, 1% and 1288.6%, versus baseline. It saves energy and reduces emissions. Virgin materials are substituted and water is saved (Zaman and Lehmann, 2013).

The National Policy on Solid Waste in Brazil encourages recycling and composting. Therefore, small Brazilian municipalities such as the case studied here should advance this target. Not only because it is the law, but also because it has integrated management that minimizes emissions of greenhouse gases and saves energy. Table 7 summarizes the environmental impacts of the landfill including composting, recycling and transportation. This is because it is related to the combustion of fossil fuel (Santos et al., 2014). This study focused more on the air dimension. While there

are other aspects that can be analyzed, the GHG emissions are most critical to decision-making.

Most municipalities that use the Cachoeira Paulista landfill are small. They have limited financial and human resources (United Nations Population Fund, 2007). Thus, it is a necessary consortium and intermunicipal cooperation is needed to create recycling and composting programs. Other technical aspects have positive effects as recommended by the Department of the Environment of the State of São Paulo (Secretaria do Meio Ambiente do Estado de São Paulo, 2014). This is because this consortium allows a flexible management model, technical cooperation and joint achievements of activities. It maximizes efficient use of resources (Matos and Dias, 2011). Cooperation helps with
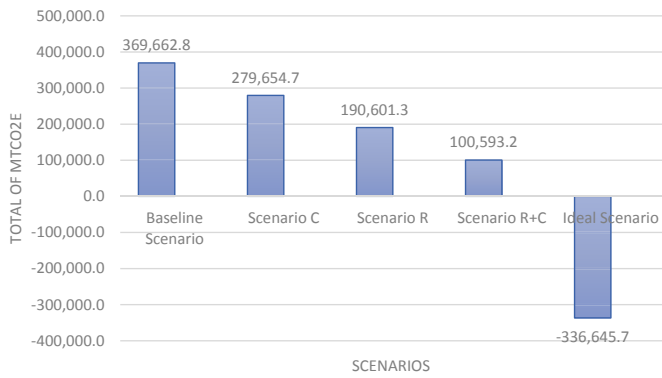
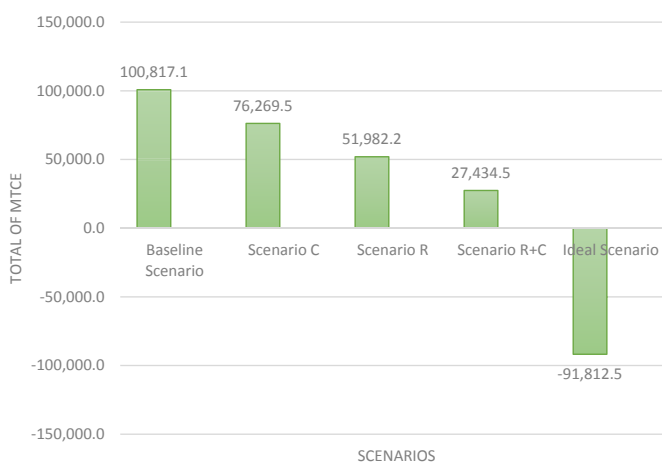**Fig. 8.** Total emission of metric tons of carbon dioxide equivalent (MTCO₂E) in each scenario.

Fig. 9. Total emission of metric tons of carbon equivalent (MTCOE) in each scenario.
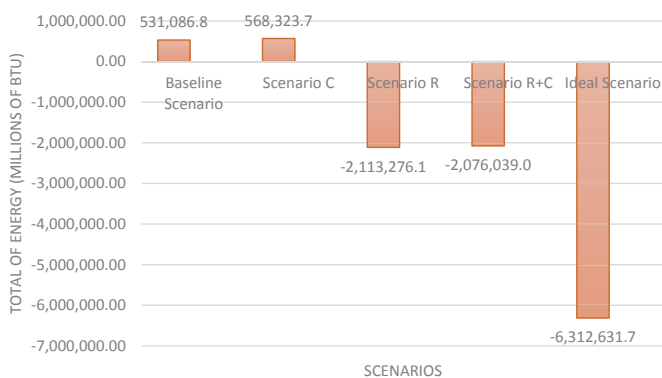

Fig. 10. Total energy consumption in millions of BTU in each scenario.

recycling—especially these municipalities—because when the municipality does not even own a landfill, adding recycling is difficult (Usui et al., 2015).

5. Conclusion

The literature and this data suggests that organic matter is a major component of solid waste. Thus, composting is an important tool in municipal solid waste management as shown by the National Policy on Solid Waste. It has an effective and positive environmental impact on CO_2 and C equivalents, but not on energy consumption. The composting scenario for the municipalities of this study reduces GHG by 24.3% versus the current situation.

Therefore, it is important to integrate composting with others treatment tools for municipal solid waste management such as recycling. Because recycling has an effective and positive environmental impact, reducing the emission of greenhouse gases also saves energy because it reintegrates materials into the life cycle of products and thus reduces raw material extraction. This requires a high amount of energy. The scenario of recycling contributes to a reduction of 48.4% of GHG and 497.9% in energy savings compared to baseline scenario.

All alternative scenarios had positive impacts, but the scenario with the integrated management demonstrates that greater positive impacts will reduce GHG by 78.8% and save 490.9% in energy versus baseline. The current situation using just the landfill, which has great potential for greenhouse gas emissions, should be changed. However, this is limited by costs and social impacts (Aprilia and Tezuka, 2013).

Importantly, this approach can generate carbon credits. This would reduce GHG by 191% and save 1288.6% energy versus baseline. Although it is an almost utopian scenario, it should be considered an ideal target for total quality management.

Note also that recycling and composting also benefit the landfill because it increases its lifetime due to decreased waste destination. Therefore, the integrated management for municipal solid waste is the best scenario for minimizing negative environmental impacts. It should be considered in the decision-making of municipal management of solid waste.

Brazilian municipalities must elaborate their Solid Waste Integrated Management Plan based on NPSW and Zero Waste goals with targets of reduction, reuse, selective collection, and recycling/composting reduce the waste disposed in soil. This plan uses scenario building as a tool to plan and decide on the generating support information and reaching targets.

One limitation of this study is that methane (CH_4) and nitrous oxide (N_2O) emissions from compost are not included due the version of model used—this results in biogenic CO_2 emissions because of decomposition. Biogenic CO_2 is not counted as a GHG in the Inventory.

Future studies may also improve the scenarios approached here with economic aspects including capital costs to reach each

Table 7
Summary of environmental impacts of waste treatments.

Environmental sink	Dumping/Landfill	Composting	Recycling	Transport
Air	CO_2, CH_4, odor, noise, VOCs, GHGs (CO_2, CH_4, N_2O)	Odor, GHGs (minor)	GHGs (minor)	CO_2, SO_2, NO_x, odor
Soil	Heavy metals, organic compounds	Minor impact	Landfilling of residues	—
Water	Leachate, heavy metals, organic compounds	Leachate	Wastewater from processing	Fallout of atmospheric pollutants (e.g., nitrate)

GHG, greenhouse gas; PCB, polychlorinated biphenyl; VOC, volatile organic compound.
Source: Adapted from Vergara and Tchobanoglous (2012).

scenario and to verify the economic feasibility. Another important and necessary study is the anaerobic digestion modeling due to the huge biodegradable materials generation in Brazil and biogas collection from landfills for energy recovery.

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