**UNIVERSITY OF SÃO PAULO
SÃO CARLOS SCHOOL OF ENGINEERING**

PRISCILA DE MORAIS LIMA

**Life Cycle Assessment of current and prospective waste management
systems in Brazil**

Corrected Version (Versão Corrigida)

São Carlos

2019

PRISCILA DE MORAIS LIMA

**Life Cycle Assessment of current and prospective waste management
systems in Brazil**

Doctoral thesis presented at São Carlos
School of Engineering, University of São
Paulo in partial fulfillment of the
requirements for the Degree of Doctor in
Science: Hydraulics and Sanitary
Engineering.

Supervisor: Prof. Dr. Valdir Schalch
Co-supervisor: Prof. Dra. Paula Loureiro
Paulo

Corrected Version (Versão Corrigida)

São Carlos

2019

AUTORIZO A REPRODUÇÃO TOTAL OU PARCIAL DESTE TRABALHO,
POR QUALQUER MEIO CONVENCIONAL OU ELETRÔNICO, PARA FINS
DE ESTUDO E PESQUISA, DESDE QUE CITADA A FONTE.

Ficha catalográfica elaborada pela Biblioteca Prof. Dr. Sérgio Rodrigues Fontes da
EESC/USP com os dados inseridos pelo(a) autor(a).

L7321 Lima, Priscila de Moraes
 Life Cycle Assessment of current and prospective
waste management systems in Brazil / Priscila de Moraes
Lima; orientador Valdir Schalch; coorientadora Paula
Loureiro Paulo. São Carlos, 2019.

 Tese (Doutorado) - Programa de Pós-Graduação em
Engenharia Hidráulica e Saneamento e Área de
Concentração em Hidráulica e Saneamento -- Escola de
Engenharia de São Carlos da Universidade de São Paulo,
2019.

 1. Municipal Solid Waste (MSW). 2. environmental
assessment. 3. developing countries. 4. sustainability.
5. EASETECH. 6. Solid Waste National Policy (PNRS). I.
Título.

FOLHA DE JULGAMENTO

Candidata: Bacharel **PRISCILA DE MORAIS LIMA**.

Título da tese: "Avaliação do ciclo de vida de sistemas de gerenciamento de resíduos sólidos atuais e futuros no Brasil".

Data da defesa: 15/04/2019.

Comissão Julgadora:

Resultado:

Prof. Associado **Valdir Schalch**
(Orientador)

(Escola de Engenharia de São Carlos/EESC)

APROVADA

Prof. Dr. **Marco Aurélio Soares de Castro**
(Universidade Estadual de Campinas/UNICAMP)

APROVADA

Profa. Dra. **Kátia Sakihama Ventura**
(Universidade Federal de São Carlos/UFSCar)

APROVADA

Profa. Dra. **Marjolly Priscilla Bais Shinzato**
(Universidade Federal de Mato Grosso do Sul/UFMS)

Aprovado

Prof. Dr. **Geraldo Antônio Reichert**
(Departamento Municipal de Limpeza Urbana/DMLU)

APROVADA

Coordenador do Programa de Pós-Graduação em Engenharia Hidráulica e Saneamento:

Prof. Dr. **Eduardo Mario Mendiando**

Presidente da Comissão de Pós-Graduação:

Prof. Titular **Murilo Araujo Romero**

ACKNOWLEDGEMENTS

First of all, I owe everything I have and all that I am to God. For the gift of life and the opportunities I encountered, and also for giving me strength to keep going even and especially when it was too hard, I am deeply grateful. It is extremely rewarding to see a little over three years of hard work and learning paying off and giving amazing results, I had a lot of people by my side during this time, and I hope I can put in words what they truly mean to me.

I cannot describe the gratitude towards my family, especially my parents Emanuel and Eda and my sister Jéssica. For all the emotional and financial support and for always being by my side backing up all my decisions and celebrating all my big and small accomplishments. To my grandparents, uncles, aunts and cousins for the love and laughter we always shared whenever back home.

My deepest gratitude to all the Professors and researchers that helped me through this doctorate. Prof. Valdir Schalch from University of São Paulo (USP) for believing and trusting my project and for giving me the freedom to pursue all my ambitions. Profa. Paula Loureiro Paulo from the Federal University of Mato Grosso do Sul (UFMS) for once again trusting me and for the incredible support both technical and emotional, for always being there for me and for being an incredible human being. Prof. Henrik Wenzel and the Life Cycle Engineering (LCE) group at the University of Southern Denmark (SDU) for my stay as a guest PhD, for making it so welcoming and one of the best experiences of my life. And Ciprian Cimpan for embracing my cause, trusting my project and guiding me by the hand throughout the modelling and publications.

I am sincerely thankful for the good relationship that I built with the staff at Deméter Engenharia when working there, that resulted in an amazing collaboration afterwards. A big thanks for sticking by my side, providing me data and location support whenever needed, especially Fernanda, Lucas, Neif, Matheus, Mário, Jorge and Priscilla.

Huge thanks to my friends as well, the ones back home, the ones I made in my short time in São Carlos and everyone that was part of my journey in Denmark. A special thanks to my forever flatmate Tamara for being my family in DK and sharing such great moments and emotions with me. My officemates Maud, Kasper and Anders for making the hard days at the office fun and for all the advices and help. Zhi and Dmitry for closing up our cool LCE gang and sharing so many fun moments together. Also Thalles for being my closest link to Brazil, for being such a “partner in crime”, for the trips, food and coffee we shared together. I am also

thankful to other friends I made in Odense, and the people that were part of my every day life, making life away from home a lot easier, especially Ruben, Carina, Magnus and Jakob.

Special gratitude to all the friends I left back home and never left my side, I am forever grateful to Giovana, Luciana and Luana for keeping up with all my craziness and “unique” lifestyle and still being my best friends and giving me emotional support, and Raphaella for being a truthful friend in São Carlos.

Finally, I would like to acknowledge the Brazilian funding agency Coordination for the Improvement of Higher Education Personnel (Capes) for the PhD funding, USP and SDU for the infrastructure and technical support.

RESUMO

LIMA, Priscila de Moraes. **Avaliação do Ciclo de Vida de Sistemas de Gerenciamento de Resíduos Sólidos Atuais e Futuros no Brasil**. Tese [Doutorado em Engenharia Civil (Hidráulica e Saneamento)] – Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, 2019.

O aumento da geração de Resíduos Sólidos Urbanos (RSU) juntamente com a atual gestão inadequada de resíduos e a promulgação da Política Nacional de Resíduos Sólidos (PNRS) em 2010, trouxeram uma maior preocupação em relação ao assunto nos municípios brasileiros. Apesar de todas as exigências da Política, os locais de disposição inadequados ainda representam 40% do destino dos resíduos coletados no Brasil. Além disso, apenas cerca de 3,6% dos recicláveis são atualmente recuperados. Campo Grande é a capital do estado de Mato Grosso do Sul e possui aterro sanitário com apenas dois anos de vida útil. O município publicou recentemente sua nova ferramenta para auxiliar a gestão de resíduos sólidos – o Plano de Coleta Seletiva (PCS), que é composto por planejamento e metas para os próximos 20 anos. Diante desta situação, o objetivo desta pesquisa foi analisar e comparar diferentes sistemas de manejo de resíduos para o Brasil (**Capítulo 2**) e Campo Grande (**Capítulo 3**). Foi utilizada a Avaliação do Ciclo de Vida (ACV) consequential, com o software EASETECH para modelagem. Os resultados gerais mostraram que os locais de disposição inadequados (ou seja, lixões) possuem os maiores impactos ambientais devido à falta de tratamento do gás de aterro e do lixiviado. A combinação de altas taxas de reciclagem e baixa quantidade de resíduos dispostos em aterros apresentou bom desempenho global em ambos os casos. De todos os cenários avaliados, o melhor desempenho alcançado foi através da digestão anaeróbia dos resíduos orgânicos, com a utilização de biogás como substituto de combustível, combinada com uma unidade de triagem e um tratamento mecânico biológico de resíduos misturados, e combustível derivado de resíduos destinado a fornos de cimenteiras evitando a combustão de coque. Em conclusão, a conscientização ambiental deve ser direcionada à população e a responsabilidade conferida aos tomadores de decisão para as mudanças que precisam ocorrer visando a redução dos impactos ambientais dos sistemas e o cumprimento da PNRS.

Palavras-chave: Resíduos Sólidos Urbanos (RSU), avaliação ambiental, países em desenvolvimento, sustentabilidade, EASETECH, Política Nacional de Resíduos Sólidos (PNRS).

ABSTRACT

LIMA, Priscila de Moraes. **Life Cycle Assessment of current and prospective waste management systems in Brazil**. Thesis [Doctorate in Civil Engineering (Hydraulics and Sanitation)] – São Carlos School of Engineering, University of São Paulo, São Carlos, 2019.

The increase of Municipal Solid Waste (MSW) generation along with the current inadequate waste management and the issue of the Solid Waste National Policy (PNRS) in 2010, have brought a bigger concern in regards to the matter to Brazilian municipalities. Besides all the demands of the Policy, improper waste disposal sites still represent 40% of the destination of the waste collected in Brazil. In addition, only about 3.6% of recyclables are currently recovered. Campo Grande is the state capital of Mato Grosso do Sul and has a sanitary landfill with two more years of lifespan. The city has recently published its new tool to aid waste management – the Selective Collection Plan (PCS), which is comprised of planning and goals for the next 20 years. Facing this situation, the aim of this research was to analyze and compare different waste management systems for Brazil (**Chapter 2**) and Campo Grande (**Chapter 3**). A consequential Life Cycle Assessment (LCA) was employed, with the software EASETECH for modelling. The general results showed that the improper disposal sites (i.e. dumps) have the highest environmental impacts due to the untreated landfill gas and leachate. The combination of high recycling rates and low amounts of waste disposed in landfills presented overall good performance in both cases. From all the scenarios assessed, the best performance was achieved by anaerobic digestion of the biowaste, with biogas utilization as fuel substitute, combined with a material recovery facility and a mixed waste mechanical biological treatment, with residue derived fuel directed to cement kilns avoiding coke combustion. In conclusion, the environmental awareness must be raised towards the population and the decision-makers are entitled to the changes that need to happen in order to decrease the environmental impacts of the systems and comply with the Brazilian waste legislation.

Keywords: Municipal Solid Waste (MSW), environmental assessment, developing countries, sustainability, EASETECH, Solid Waste National Policy (PNRS).

LIST OF TABLES

Table 1-1 – Normalization factors ILCD recommended.....	30
Table 1-2– Summary table for the foreground scenarios	31
Table 1-3 – Waste composition for Brazil.....	57
Table 1-4 – Collection and transportation vehicles, travelled distances and fuel consumptions.	58
Table 1-5 – Transfer coefficients for MRFs low and high tech.	59
Table 1-6 – Landfill parameters used in EASETECH.	60
Table 1-7– Technology description of biological treatment used in the study.	63
Table 1-8 - Transfer coefficients for wet waste pre-treatment and the pulper technology.	64
Table 1-9– Parameters adopted for the biological treatment processes (biogas upgrading and combustion not included here).	65
Table 1-10 – Emissions from combustion of biogas to electricity and heat.....	66
Table 1-11 - Transfer coefficients sorting MBT simple.....	67
Table 1-12 - Transfer coefficients sorting MBT advanced	68
Table 1-13– Parameters adopted for the MBT processes.....	70
Table 1-14 – Recovery efficiencies and market ratio for the recycling processes.....	72
Table 1-15 – Petroleum coke chemical characteristics and transfer coefficients to the air compartment.	74
Table 1-16– Parameters and description of the sensitivity analysis performed.	75
Table 1-17- Electricity mix and ecoinvent processes used for the sensitivity analysis.....	75
Table 1-18 - Characterized LCA results for scenarios 1.	76
Table 1-19 - Characterized LCA results for scenarios 2.	78
Table 1-20 - Characterized LCA results for scenarios 3.	81
Table 1-21– Normalized net results in mili Person Equivalents (mPE) for Climate Change (GWP), Ozone Depletion (ODP), Human Toxicity, Cancer Effects (HT, CE), Human Toxicity, non-Cancer Effects (HT, non CE), Particulate Matter (PT), Photochemical Ozone Formation (POF), Terrestrial Acidification (TAD), Eutrophication Terrestrial (EPT), Eutrophication Freshwater (EPF), Eutrophication Marine (EPM), Ecotoxicity Freshwater (ECF) and Depletion of Abiotic resources, Mineral fossil and Renewable (DAMR).	85
Table 1-22 - Characterized sensitivity results for all parameters modified.....	90
Table 2-1 – Summary of gravimetric compositions for the waste streams included in this work; given in percentage wet weight.	101

Table 2-2 – Gravimetric composition of each stream considered for the modelling.	102
Table 2-3 – Total urban population and per sector in the municipality projected until 2037.	103
Table 2-4 – Household waste amounts per sector for 2017.	104
Table 2-5– Summary waste generation in tonnes per year for the milestone years, and related urban population.	104
Table 2-6 – Potential for dry recyclables of HHW and CMW, targets for each selective collection and its respective masses.	106
Table 2-7 – Waste projections per stream from 2017 to 2037. HHW (Household waste) is the sum of regular, selective, ecopoints and biowaste.	107
Table 2-8 – Summary of the main foreground scenarios and variations, in the different milestone years.	110
Table 2-9 – Electricity mix and ecoinvent processes used for current policies trend.	112
Table 2-10– Destination and transport distance for treatment outputs.	121
Table 2-11 – MRF transfer coefficients for 2017 and 2022.	122
Table 2-12 – MRF transfer coefficients for 2027.	122
Table 2-13 – MRF transfer coefficients for 2032.	123
Table 2-14 – MRF transfer coefficients for 2037.	124
Table 2-15 – Normalized net impacts in 1000*PE for all scenarios for: Climate Change (GWP), Ozone Depletion (ODP), Human Toxicity, Cancer Effects (HT, CE), Human Toxicity, non Cancer Effects (HT, non CE), Particulate Matter (PT), Photochemical Ozone Formation (POF), Terrestrial Acidification (TAD), Eutrophication Terrestrial (EPT), Eutrophication Freshwater (EPF), Eutrophication Marine (EPM), Ecotoxicity Freshwater (ECF) and Depletion of Abiotic resources, Mineral fossil and Renewable (DAMR).	129
Table 2-16 - Characterized net LCA results for all scenarios.	130
Table 2-17 – Process contribution, full functional unit – Characterization LCA results for GWP (kg CO ₂ eq.).	133
Table 2-18 - Process contribution, functional unit normalized to 1 tonne – Characterization LCA results for GWP (kg CO ₂ eq.). Red suggests the worst overall performing scenario and green the best overall performing scenario.	134
Table A-1 – Brazilian municipalities with its states and population that were used for the Brazilian average gravimetric composition.	158
Table A-2 – Average gravimetric composition of the Brazilian Municipalities before the informal sector.	159

Table B-1 – Gravimetric composition for each sector of the regular waste collection in Campo Grande.	160
Table B-2 –Gravimetric composition for each sector of the selective collection in Campo Grande (population covered by separate collection schemes).....	161

LIST OF FIGURES

Fig. 1-1 - Scenario 1.a. Semi-controlled dumps.....	34
Fig. 1-2 - Landfill template.....	35
Fig. 1-3 - Scenario 1.e. Waste-to-Energy (WtE) by means of moving grate combustion.....	36
Fig. 1-4 - Scenario 2.a. Dry stream sorted in a simple MRF and wet stream sanitary landfilling.	37
Fig. 1-5 - Scenario 2.b. Dry stream sorted in an advanced MRF and wet stream sanitary landfilling.	38
Fig. 1-6 - Scenario 2.c(w). Open air composting	39
Fig. 1-7 - Windrows composting template.	40
Fig. 1-8 - Fertilizer substitution template.	41
Fig. 1-9 - Scenario 2.c(e). Dry stream sorting and wet stream pre-treatment and wet digestion, biogas to electricity production.	42
Fig. 1-10 - Enclosed composting template.	43
Fig. 1-11 - Scenario 2.d. Dry stream sorting and wet stream dry digestion, biogas to electricity production.....	44
Fig. 1-12 – Anaerobic digestion with substitution template.....	45
Fig. 1-13 - Scenario 2.d(u). Biogas upgraded and used as vehicle fuel	46
Fig. 1-14 - Anaerobic digestion with fuel upgrading template.....	47
Fig. 1-15 - Scenario 2.e. Dry stream sorting and wet stream pre-treatment and wet digestion, biogas to electricity production.	48
Fig. 1-16 - Scenario 2.e(u). Dry stream sorting and wet stream pre-treatment and wet digestion, biogas upgraded and used as vehicle fuel.....	49
Fig. 1-17 - Scenario 3.a. Simple Aerobic MBT.....	50
Fig. 1-18 - RDF to cement production template.....	51
Fig. 1-19 - Scenario 3.b. Advanced Anaerobic-aerobic MBT.....	52
Fig. 1-20 - Scenario 3.b(u). Biogas upgraded and used as vehicle fuel.	53
Fig. 1-21 - Scenario 3.c. Simple Biological drying MBT.	54
Fig. 1-22 - Biodrying template.	55
Fig. 1-23 - Scenario 3.d. Advanced Biological drying MBT.	56
Fig. 1-24 – Normalized results in mili Person Equivalents (mPE) for Category 1 systems for: Climate Change (GWP), Ozone Depletion (ODP), Human Toxicity, Cancer Effects (HT, CE), Human Toxicity, non Cancer Effects (HT, non CE), Particulate Matter (PT), Photochemical	

Ozone Formation (POF), Terrestrial Acidification (TAD), Eutrophication Terrestrial (EPT), Eutrophication Freshwater (EPF), Eutrophication Marine (EPM), Ecotoxicity Freshwater (ECF) and Depletion of Abiotic resources, Mineral fossil and Renewable (DAMR).....	86
Fig. 1-25- Normalized results in mili Person Equivalents (mPE) for Category 2 systems for Climate Change (GWP), Ozone Depletion (ODP), Human Toxicity, Cancer Effects (HT, CE), Human Toxicity, non Cancer Effects (HT, non CE), Particulate Matter (PT), Photochemical Ozone Formation (POF), Terrestrial Acidification (TAD), Eutrophication Terrestrial (EPT), Eutrophication Freshwater (EPF), Eutrophication Marine (EPM), Ecotoxicity Freshwater (ECF) and Depletion of Abiotic resources, Mineral fossil and Renewable (DAMR).....	87
Fig. 1-26- Normalized results in mili Person Equivalents (mPE) for Category 3 systems for Climate Change (GWP), Ozone Depletion (ODP), Human Toxicity, Cancer Effects (HT, CE), Human Toxicity, non Cancer Effects (HT, non CE), Particulate Matter (PT), Photochemical Ozone Formation (POF), Terrestrial Acidification (TAD), Eutrophication Terrestrial (EPT), Eutrophication Freshwater (EPF), Eutrophication Marine (EPM), Ecotoxicity Freshwater (ECF) and Depletion of Abiotic resources, Mineral fossil and Renewable (DAMR).....	89
Fig. 1-27- Sensitivity results in kg CO ₂ eq. for Climate Change (GWP).....	92
Fig. 1-28- Impact for the average management of MSW collected in Brazil in 2016, considering the ratios given in the introduction (17% semi-controlled dumps, 25% controlled dumps and respectively 54% sanitary landfills with gas flaring).	93
Fig. 2-1 – Socio-economic sectors by scores in the urban perimeter of the municipality. Source: DMTR, 2018.....	100
Fig. 2-2 –Waste generation per capita for the different sectors in Campo Grande. Source: Adapted from Manzi (2017).	103
Fig. 2-3 – Process flow of the systems analyzed. Notes: (1) the flow colors denote the main treatment; (2) b2022 and b2032 refer to the alternative scenarios plus the year the technology is inserted in the system.....	111
Fig. 2-4– Electricity generation projection for Brazil according to IEA (2013) and marginal electricity mix for each milestone year with corresponding GWP factors.....	111
Fig. 2-5 – “a” series of scenarios for 2017.	114
Fig. 2-6 – a series scenarios for 2022 and 2027.	115
Fig. 2-7 - a series of scenarios for 2032 and 2037.....	116
Fig. 2-8 – 2017 scenario in b series.	118
Fig. 2-9 – Scenarios 2022 and 2027 in the b series.	119
Fig. 2-10 – 2032 and 2037 scenarios for b series.	120

Fig. 2-11 – Sankey diagram with the MSW flows for 2017 (current system) and 2037 (both development scenarios).	126
Fig. 2-12 – Recycling rates achieved from 2017 to 2037.....	127
Fig. 2-13– Normalized impacts in 1000*PE throughout the years from a series and b series systems for: Climate Change (GWP), Ozone Depletion (ODP), Human Toxicity, Cancer Effects (HT, CE), Human Toxicity, non Cancer Effects (HT, non CE), Particulate Matter (PT), Photochemical Ozone Formation (POF), Terrestrial Acidification (TAD), Eutrophication Terrestrial (EPT), Eutrophication Freshwater (EPF), Eutrophication Marine (EPM), Ecotoxicity Freshwater (ECF) and Depletion of Abiotic resources, Mineral fossil and Renewable (DAMR).	128
Fig. 2-14 – Characterized GWP impacts in absolute values and per tonne of waste generated. Note: Collection represents the sum of emissions from regular and selective; Landfill represents the net of emissions minus carbon storage; Recycling represents the net of recycling emissions minus savings of primary production; Energy savings represents the sum of all energy saved in the system (e.g. from landfill gas and steam in the industry).....	135

LIST OF ABBREVIATIONS AND ACRONYMS

ABRELPE	Brazilian Association of Public Cleaning and Special Waste Companies	Associação Brasileira de Empresas de Limpeza Pública e Resíduos Especiais
AC	Avoided Coke	Coque evitado
AD	Anaerobic Digestion	Digestão Anaeróbia
BaU	Business as Usual	
Biowaste	Biodegradable waste	Resíduo biodegradável
BREF	Best Available Techniques for the Waste Treatment Industries	Melhores Técnicas Disponíveis para as Indústrias de Tratamento de Resíduos
Capes	Coordination for the Improvement of Higher Education Personnel	Coordenação de Aperfeiçoamento de Pessoal de Nível Superior
CEMPRE		Compromisso Empresarial para Reciclagem
CH ₄	Methane	Metano
CMW	Commercial/Institutional Waste	Resíduos comerciais e institucionais
CNG	Compressed Natural Gas	Gás natural comprimido
CO ₂ eq.	Carbon dioxide equivalent	Dióxido de carbono equivalente
CSTR	Continuous Stirred Tank Reactors	Tanques reatores agitados continuamente
DAMR	Depletion of abiotic resources, mineral, fossils and renewables	Depleção de recursos abióticos, minerais, fósseis e renováveis
DMTR		Deméter Engenharia
EASETECH	Environmental Assessment of Solid Waste Systems and Technologies	Avaliação ambiental de sistemas e tecnologias de resíduos sólidos
EC-JRC	European Commission – Joint Research Centre	Comissão europeia – centro de pesquisa conjunta
ECF	Ecotoxicity Freshwater	Ecotoxicidade aquática
EPF	Eutrophication Freshwater	Eutroficação aquática
EPM	Eutrophication Marine	Eutroficação marinha
EPT	Eutrophication Terrestrial	Eutroficação terrestre

FU	Functional Unit	Unidade funcional
GHG	Greenhouse Gas	Gás de efeito estufa
GWP	Global Warming Potential	Potencial de aquecimento global
HDPE	High Density Polyethylene	Polietileno de Alta Densidade
HT, CE	Human Toxicity, Cancer Effects	Toxicidade humana, efeitos cancerígenos
HT, non CE	Human Toxicity, non Cancer Effects	Toxicidade humana, efeitos não cancerígenos
HHW	Household Waste	Resíduo domiciliar
IBGE	Brazilian institute of geography and statistics	Instituto Brasileiro de Geografia e Estatística
ICE	Internal Combustion Engines	Motores de combustão interna
IEA	International Energy Agency	Agência internacional de energia
ILCD	International Reference Life Cycle Data System	Sistema internacional de dados de referência do ciclo de vida
ISO	International Standard Organization	Organização internacional para padronização
IWM	Integrated Waste Management	Gerenciamento integrado de resíduos
IWMS	Integrated Waste Management System	Sistema de gerenciamento integrado de resíduos
k	Decay rate	Taxa de decaimento
LCA	Life Cycle Assessment	Avaliação do ciclo de vida
LCE	Life Cycle Engineering	Engenharia do ciclo de vida
LCI	Life Cycle Inventory	Inventário do ciclo de vida
LCIA	Life Cycle Impact Assessment	Avaliação de impactos do ciclo de vida
LDPE	Low Density Polyethylene	Polietileno de Baixa Densidade
LFG	Landfill Gas	Gás de aterro
LNG	Liquified Natural Gas	Gás natural líqüefeito
MBT	Mechanical Biological Treatment	Tratamento mecânico biológico
MCF	Methane Correction Factor	Taxa de correção de metano
MJ	Mega Joule	Mega Joule

MMA	Ministry of environment	Ministério do Meio Ambiente
mPE	Mili Person Equivalent	Mili pessoas equivalentes
MRF	Material Recovery Facility	Instalações de recuperação de materiais
MS		Mato Grosso do Sul
MSW	Municipal Solid Waste	Resíduos sólidos municipais
N ₂ O	Nitrous Oxide	Óxido nitroso
NH ₃	Ammonia	Amônia
NMVOC	Non-Methane Volatile Organic Compound	Compostos orgânicos voláteis com exceção do metano
NO _x	Nitrogen Oxides	Óxidos de nitrogênio
ODP	Ozone Depletion	Depleção da camada de ozônio
PC	Post-composting	Pós compostagem
PCS	Selective collection plan	Plano de Coleta Seletiva
PE	Person Equivalent	Pessoa equivalente
PET	Polyethylene Terephthalate	Politereftalato de Etileno
PMCG		Prefeitura Municipal de Campo Grande
PNMC	National policy on climate change	Política Nacional de Mudanças Climáticas
PNRS	Solid Waste National Policy	Política Nacional de Resíduos Sólidos
POF	Photochemical Ozone Formation	Formação fotoquímica de ozônio
PP	Polypropylene	Polipropileno
PT	Particulate Matter	Material particulado
RDF	Residue Derived Fuel	Combustível derivado de resíduos
RTO	Regenerative Thermal Oxidation	Oxidação térmica regenerativa
SDU	Southern University of Denmark	Universidade do sul da Dinamarca
SNIS		Sistema Nacional de Informações sobre Saneamento
TAD	Terrestrial Acidification	Acidificação terrestre
TS	Total Solids	Sólidos totais

UFMS	Federal university of Mato Grosso do Sul	Universidade Federal do Mato Grosso do Sul
USP	University of São Paulo	Universidade de São Paulo
WISARD	Waste Integrated Systems for Assessment of Recovery and Disposal	Sistemas integrados de resíduos para avaliação de recuperação e disposição
WRATE	Waste Resources Assessment Tool for the Environment	Ferramenta de avaliação de recursos de resíduos para o meio ambiente
WtE	Waste to Energy	Energia proveniente de resíduos

TABLE OF CONTENTS

AKNOWLEDGEMENTS.....	III
RESUMO.....	V
ABSTRACT	VI
LIST OF TABLES.....	VII
LIST OF FIGURES.....	X
LIST OF ABBREVIATIONS AND ACRONYMS.....	XIII
TABLE OF CONTENTS	XVII
CHAPTER 1 - GENERAL INTRODUCTION	19
CHAPTER 2 - ENVIRONMENTAL ASSESSMENT OF EXISTING AND ALTERNATIVE OPTIONS FOR MANAGEMENT OF MUNICIPAL SOLID WASTE IN BRAZIL	25
1 INTRODUCTION	26
1.1 Evaluation of MSW management strategies in Brazil	26
1.2 Study objectives	28
2 MATERIALS AND METHODS.....	29
2.1 LCA methodology	29
2.2 Description of alternative systems (foreground scenarios).....	31
2.3 Life cycle inventory (LCI).....	57
2.4 Sensitivity Analysis	74
3 RESULTS	75
3.1 Overall comparison of systems and impact categories	84
3.2 Process contribution analysis.....	85
3.3 Sensitivity results	90
4 DISCUSSION	92
5 CONCLUSIONS.....	94
REFERENCES.....	95

CHAPTER 3 - LIFE CYCLE ASSESSMENT OF PROSPECTIVE MSW MANAGEMENT BASED ON INTEGRATED MANAGEMENT PLANNING IN CAMPO GRANDE, BRAZIL	96
1 INTRODUCTION	97
2 MATERIALS AND METHODS	99
2.1 Study area and reference data.....	99
2.2 LCA methodology	108
2.3 Scenarios for future development of MSW management.....	109
2.4 Life Cycle iInventories (LCIs) of collection and treatment processes.....	121
3 RESULTS	125
3.1 Waste flows and recycling over the study period	125
3.2 Life cycle impact assessment results	127
3.3 Specific contributions to climate change.....	132
4 DISCUSSION	137
4.1 Further limitations and uncertainty	138
4.2 Barriers to sustainable MSW management	139
5 CONCLUSIONS.....	140
REFERENCES.....	141
CHAPTER 4 - GENERAL CONCLUSIONS	142
REFERENCES	144
APPENDICES.....	157
APPENDIX A.....	158
APPENDIX B.....	160

CHAPTER 1 - GENERAL INTRODUCTION

Municipal Solid Waste (MSW, resíduos sólidos urbanos in Portuguese) refers to, according to the Brazilian Solid Waste National Policy (PNRS – Federal law n. 12,305/2010), all the remains from domestic activities and urban houses (household waste), from street sweeping, cleaning of public places and roads and other urban cleaning services (urban cleaning waste) (Brasil, 2010). In emerging economies the authorities face a big challenge when planning MSW management due mainly to: the waste generation that tends to increase; the municipal financial difficulties associated with high costs of management actions; the lack of understanding of all factors that influence the different steps of the management; and the need to link all the steps in order to make the system work (Guerrero, Maas, & Hogland, 2013).

Integrated management refers to the combination of different collection and treatment methods to deal with all materials in the system, from generation to disposal, in an environmentally effective, socially acceptable and economically feasible way (McDougall, White, Franke, & Hindle, 2001). Improper waste management can cause groundwater contamination, disease outbreaks, climate change, air quality decay, among other environmental and human health impacts (Schalch, Leite, Fernandes Junior, & De Castro, 2002). The decomposition of the waste itself produces methane, which directly contributes to global warming when not collected and treated. Indiscriminate dumping can contaminate ground and surface water and the soil from the leachate; also, it can clog drains in urban areas when carried by the rain around. Besides that, exposed waste attracts vectors, such as rodents and insects, which can spread different types of diseases (e.g. malaria and yellow fever). Furthermore, when waste is burned in an uncontrolled manner, it contributes significantly to air pollution due to the dioxins produced (Alam & Ahmade, 2013; T. Christensen, 2011; Ferreira & Anjos, 2001).

Brazil is one of the largest (5th) and most populated (5th) countries in the world, with nearly 210 million inhabitants in the beginning of 2019 (IBGE, 2019). Even though the country is emerging and finding its way between the developed economies, it is still facing big challenges in relation to Integrated Solid Waste Management (ISWM). The most recent data available estimated a total waste generation of 78.3 million tonnes of MSW in 2016, whilst around 90% of it gets collected only 58.4% is properly disposed in sanitary landfills, leaving 41.6% to controlled landfills and open dumps (ABRELPE, 2017). The PNRS established that by 2014 only the rejects could be disposed in sanitary landfills, however, the deadline was not met and not only potentially recoverable waste continues to be disposed in landfills, but

Brazilians are still improperly dumping nearly 34,000 tonnes of waste every day (ABRELPE, 2017). Furthermore, the legislation determined the increase of selective collection and reverse logistics coverage, the disposal of only rejects in landfills (i.e. after all treatment options have been exhausted) and the inclusion of waste pickers in the strategical planning (with incentives to formalize the activity through cooperatives) (Deus, Battistelle, & Silva, 2017).

Besides the rather alarming statistics, the country has been taking small steps towards a more sustainable waste management. Considering that the waste policy was only issued in 2010, the actions have improved since then. The waste collection is nearly 100% now and the initiatives of selective waste collection are also raising. Almost 70% of the Brazilian municipalities (3,878 out of 5,570) have some kind of selective collection initiative, which represents an increasing concern on the subject (ABRELPE, 2017). Waste pickers are responsible for 90% of the recyclables collection, and they are known to play a big role in the entire waste recovery chain (Aquino, Castilho Jr., & Pires, 2009). Aside from the sanitary landfills, which were reported to be 679 in 2015, there were 846 sorting units distributed all over Brazil in the same year, 65 composting plants and 18 incineration plants, which are mainly used for hazardous waste (SNIS, 2016).

Waste incineration is an oxidation process, a thermal conversion of the matter into energy, ash and flue gas in very high temperatures (CEMPRE, 2010). It has become very popular, especially in developed countries, as the Waste-to-Energy (WtE) technology with extensive processes and emission control systems, contributing to savings in fossil fuels consumption (T. Christensen, 2011). The composting technique is a resource used to recycle domestic organic waste resulting in a compost with agricultural fertilizer properties and/or degraded soil agent. The high temperature reached by the system must be responsible for the reduction of pathogenic microorganisms present at the beginning of the process, thus ensuring the microbiological quality of the compound without risk of contamination (Heck *et al.*, 2013). Anaerobic Digestion (AD) is also a process of recycling matter, in which organic compounds are degraded by the action of anaerobic microorganisms until the formation of a mixture where carbon dioxide and methane (biogas, that can be transformed into energy) predominate, generating a residue that can be used in agriculture (digest, after a maturation/compost like process) (CEMPRE, 2010).

Mechanical Biological Treatment (MBT) plants as the name suggests, combine mechanical treatment equipments (such as screen, sieves and magnets) with biological technologies (composting, AD). It is a very complete process that leaves a small fraction to landfill disposal and recovers the so-called Residue Derived Fuel (RDF) that can be used as

fossil fuel substitute in the cement industry, for example (T. Christensen, 2011). These are common technologies employed all over the world to treat solid waste and avoid landfilling. Therefore, they should be considered as alternatives when analyzing different integrated waste management systems, combined with waste minimization, proper collection schemes, source separation, sorting units and final disposal of only the rejects as stated in the PNRS (Brasil, 2010).

Life Cycle Assessment (LCA) is a structured and internationally standardized method that quantifies all the relevant emissions, consumed resources and environmental and human health impacts related to a service or a product. It is a powerful and vital tool regarding decision-making that can complement or be complemented by other methods that are needed to improve sustainable production and consumption (EC-JRC, 2011). LCA is regulated by the International Standards Organization (ISO) in standards 14,040 and 14,044 which define four mandatory steps to be considered: objective and scope definition, inventory analysis, impact assessment and interpretation. Regarding the multi-functional processes contained in a system, there are two different approaches that can be taken, the attributional LCA, which employs allocation to solve multifunctionality, by distributing the environmental impacts throughout the inputs and outputs. And the consequential LCA, which considers system expansion and the market response to changes in the systems when determining the environmental burdens and savings (ABNT, 2016).

Over the past 30 years, LCA has been applied to assess all potential impacts of a product or service since it provides consistent assessments of the benefits and drawbacks related to a range of available alternatives (Song, Wang, & Li, 2013). Through an effective LCA it is possible to calculate a product's and/or system's environmental impacts, positive and negative ones, find improvement opportunities in the process, compare and analyze processes based on its environmental impact and justify a change in a process or product quantitatively (Williams, 2009). Furthermore, it is one of the most widely used decision support framework for waste management systems due to the environmental assessment of alternative systems and/or the identification of possible improvements in the existing ones (Koci & Trecakova, 2011).

As an LCA is a very comprehensive study that contemplate lots of data and different calculations, there are a number of distinctive tools to help the modelling process, such as Simapro, Umberto and Gabi. More specifically for waste systems LCAs, different entities have also developed tools: EASETECH, former EASEWASTE (environmental assessment of solid waste systems and technologies), IWM-2 (integrated waste management II), WISARD (waste integrated systems for assessment of recovery and disposal), WRATE (waste resources

assessment tool for the environment), among others. The generic tools include comprehensive databases, but they are not always specific for waste management treatment and they are not sensitive to the waste composition. As for the specific tools, they account for a wide range of air, water and soil pollutants and further detailing is possible within impact categories (Kulczycka, Lelek, Lewandowska, & Zarebska, 2015).

The results from an LCA can support decision-makers on planning and optimizing Integrated Waste Management System (IWMS) as verified by Liamsanguan & Gheewala (2008) in Phuket, Thailand. Using four different scenarios, the authors analyzed incineration, landfilling, source separation for recycling and anaerobic digestion to find out that source separation should be pursued possibly combined with landfill gas recovery for electricity. In addition, the authors concluded that the method (LCA) can also play a significant role in the development of future waste management strategies.

Thomas H Christensen, Simion, Tonini and Møller (2009) analyzed 40 generic MSW management scenarios considering the average European waste composition. Most of the scenarios provided negative global warming factors and overall savings in GHG emissions, and the most significant scenarios were the ones with landfill, incineration and MBT. The generic scenarios used in this research showed that, waste management besides offering safe and hygienic management of the waste, contributes to reducing the climate change effects in society and provide insight for specific systems in which the local waste composition and technologies must be assessed.

Considering the European Union as well, in the assessment of six representative member states, the global warming factor was investigated. In the analysis great benefits to the category were achieved due to the high level of energy and material recovery substituting fossil energy and raw materials production. The study also demonstrated that there are many differences between the member states due to the relative differences of waste composition, type of waste management technologies available nationally, and the average performance of the technologies even though there are very strong regulations at European level (Gentil, Clavreul, & Christensen, 2009).

In Brazil, the PNRS may have driven more studies in the field as it stated the shared responsibility for the products' life cycle throughout the production and consumption chain. Nevertheless, since 2003 waste LCA studies have been published in the country. The motivations back then were to end the open dumps and head to landfilling, however the assessments already showed that landfilling is the worst performing alternative compared to more advanced ones (Mendes, Aramaki, & Hanaki, 2004).

In Porto Alegre eight different waste management scenarios were assessed, in which the biggest environmental savings were obtained in the scenarios with either electricity generation (biological and thermal treatments) or recycling (J. D. De Lima, Juca, Reichert, & Firmo, 2014). Soares *et al.* (2017) used LCA to verify the feasibility of alternative technologies for waste disposal in Caieiras (state of São Paulo). The comparison between landfill with flare or energy recovery, MBT, incineration, and MBT combined with incineration showed that the latter is the most attractive scenario from an environmental point of view. Furthermore, the authors concluded that there are indeed alternatives for the current Brazilian waste management scenarios, but economic, political and social barriers must be overcome. In the northeast region of Brazil, the evolution of the waste management system in João Pessoa was analyzed, based on the selective collection that is carried there (door-to-door, wet and dry streams). The results showed that this type of collection improves significantly the environmental efficiency of the whole system when compared to mixed collection. Consequently, the impacts can be decreased with the improvement of household's participation in the system. Moreover, increasing recycling rates, implementing biological treatments (composting/biomethanization) for the organic fraction and improving the transportation can also reduce the overall environmental impacts for the waste systems (Ibañez-Forés, Coutinho-Nóbrega, Bovea, de Medeiros, & Barreto, 2017).

Angelo, Saraiva, Clímaco, Infante, and Valle (2017); Bernstad Saraiva, Souza, and Valle (2017); Ibañez-Forés, Bovea, Coutinho-Nóbrega, de Medeiros-García, and Barreto-Lins (2017); Leme *et al.* (2014); Leme, Rocha, Silva, Lopes, and Ferreira (2012); Mersoni and Reichert (2017); and Reichert and Mendes (2014), have also published their contributions to the field, in different regions of Brazil or for different waste streams and scenarios. The assessment of alternative waste management scenarios compared with the baseline for different municipalities in the country have been performed and demonstrated similar results in relation to the big contribution of sanitary landfills to climate change and not so significant environmental savings from waste incineration in the country, due to the green electricity matrix. Furthermore, MBT combined with AD and the replacement of fossil fuel in the cement production for RDF, presented significant improvements in several impact categories as well (Bernstad Saraiva *et al.*, 2017; Goulart Coelho & Lange, 2018; Liikanen, Havukainen, Viana, & Horttanainen, 2018; P. D. M. Lima *et al.*, 2018; Pin, Barros, Silva Lora, & dos Santos, 2018).

As waste management is locally-dependent, happening close to its waste source, LCAs are geographically representative (Bakas *et al.*, 2018). Therefore, based on the gaps in the available literature and the need to plan MSW management as determined by the PNRS, the

main objective of this doctoral research was to assess the environmental impacts of different waste technologies and streams, through consequential life cycle assessment, in order to generate information to help Brazilian decision-makers in planning and complying with the PNRS. Thus, the thesis is divided into four chapters, in which **Chapter 1** introduced the subjects with a short literature review, **Chapter 2** presents a comprehensive environmental assessment of alternatives for waste management systems in a hypothetical case study of Brazil and **Chapter 3** is a follow-up with a case study in Campo Grande, State of Mato Grosso do Sul, where it was compared the baseline and reasonable alternative scenarios for the city in a 20 years horizon, and **Chapter 4** brings the general conclusions of the doctoral research.

CHAPTER 2 - ENVIRONMENTAL ASSESSMENT OF EXISTING AND ALTERNATIVE OPTIONS FOR MANAGEMENT OF MUNICIPAL SOLID WASTE IN BRAZIL

Adapted from: **Lima, P.D.M.**, Colvero, D.A., Gomes, A.P., Wenzel, H., Schalch, V., Cimpan, C. (2018) Environmental assessment of existing and alternative options for management of municipal solid waste in Brazil. *Waste Management* 78:857–870 . doi: 10.1016/j.wasman.2018.07.007.

Abstract

Life cycle assessment (LCA) was used to evaluate and compare three different categories of management systems for municipal solid waste (MSW) in Brazil: (1) mixed waste direct disposal systems, (2) separate collection systems, based on wet-dry streams, and (3) mixed waste mechanical-biological systems, including materials recovery. System scenarios were built around main treatment techniques available and applicable in developing countries, and considered barriers as well as potential synergies between waste management and other industrial production. In the first category systems, we measured the impact magnitude of improper disposal sites (semi-controlled and controlled dumps) still used for approx. 40% of collected MSW, and found that sanitary landfills could decrease it 3-5 fold (e.g. GWP, from 1100-1200 to 250-450 kg CO₂ eq. t⁻¹ waste). As an alternative, waste incineration did not show significant benefits over sanitary landfilling, due to limitations in energy utilization and the low-carbon background electricity system. Category two of systems, revealed recycling benefits and the necessity as well as potential risks of biological treatment for wet streams. Simple wet-dry collection could result in relatively high levels of contamination in compost outputs, which should be mitigated by intensive pre- and post-treatment. Potential impact of air emissions from biological degradation processes was important even after anaerobic digestion processes. Biogas upgrading and use as vehicle fuel resulted in bigger savings compared to electricity production. Lastly, category three, mechanical-biological systems, displayed savings in most environmental impact categories, associated with materials recovery for recycling and refuse-derived fuel (RDF) production and utilization in cement manufacturing.

Keywords: Municipal Solid Waste (MSW), Life Cycle Assessment (LCA), developing countries, mechanical-biological systems, material recycling.

1 Introduction

Historic and current improper waste management in Brazil continues to cause surface and groundwater contamination, contributes to climate change, air quality decay, among other environmental and human health impacts (Rosa et al., 2017; Schalch et al., 2002). Furthermore, according to some projections, generation of MSW in Brazil is likely to increase dramatically in the near-future, in connection with rapid urbanization and economic development (Velooso, 2014).

According to the annual panorama published by ABRELPE, the current Brazilian MSW generation is in the order of 78.3 million tons per year (ABRELPE, 2017). Collection coverage reaches approx. 91% of the total waste generated and waste that is not collected is likely either dumped illegally or burned in public open spaces (Alfaia, Costa, & Campos, 2017). Brazilian waste management should follow the requirements of the PNRS (Federal Law 12,305/2010): the prohibition of inadequate waste disposal and the proposed hierarchy (avoid generation, reduction, reuse, recycling, treatment and disposal) (Brasil, 2010). Nevertheless, in 2016, 17.4% of the collected mixed MSW was still disposed in semi-controlled dumps (i.e. *lixão* – in Portuguese) which have no engineering measures (no leachate or gas management), representing only a designated open location for disposal (ABRELPE, 2017). A further 25.2% was placed in controlled dumps (i.e. *aterro controlado* – in Portuguese), with basic engineering measures such as compaction and (daily, intermediate or final) cover. Finally, 58.4% was adequately disposed of in sanitary landfills (i.e. *aterro sanitário* – in Portuguese) with all proper engineering measures (Hoornweg & Bhada-Tata, 2012).

Only 1.9% of the Brazilian municipalities have composting plants, and as for incineration, so far it has been only used for hazardous waste, such as from health care (ABRELPE, 2017; SNIS, 2017). About 70% of the municipalities have selective collection initiatives, however only 3.6% of the produced waste is actually reported as separately collected. The informal sector, i.e. waste pickers, play a significant role in separate collection, being responsible for as much as 90% of the recyclables collection in the country (Aquino et al., 2009; MMA, 2012).

1.1 Evaluation of MSW management strategies in Brazil

LCA is an internationally standardized method and widely used tool in the support of decision-making (EC-JRC, 2011). With regard to environmental impact of waste management, from a decision-making perspective, Brazil constitutes a very interesting case study. Unlike many other developing countries, Brazil's electricity production mix is predominantly

renewable (dominated by hydropower), which limits possible environmental benefits of energy-from-waste strategies. Moreover, due to a ban instated in the 1970s on diesel passenger cars and commercial vehicles with capacity inferior to 1,000 kg, today the Brazilian light vehicle fleet is made up almost entirely by the so-called flexible-fuel vehicles running on a mandatory blend of anhydrous ethanol and gasoline (ethanol share reaching 27% (by volume) in 2015) (Dallmann & Façanha, 2015). This limits to some extent possible utilization of upgraded landfill gas and biogas from anaerobic digestion as vehicle fuel.

Considering the magnitude and complexity of the problem, there are few LCA studies addressing MSW in Brazil. Of the studies available, almost all employ an attributional LCA framework, where allocation is avoided by system expansion in order to credit management systems in the case of energy and materials recovery. Most studies can also be categorized based on the assessment scope, involving: (1) theoretical scenarios for mixed waste treatment, (2) theoretical scenarios including separate collection, and (3) evolution of management in a specific area over time. Studies that assessed theoretical treatment scenarios for mixed waste were mostly concerned with the potential of energy-from-waste. Mendes et al. (2004) and Leme et al. (2014, 2012) compared scenarios based on mixed MSW landfilling (with and without energy recovery) and incineration (WtE) for the cities of São Paulo and Betim (Belo Horizonte), respectively. They found that in general incineration showed a lower environmental impact than landfilling. Nevertheless, energy recovery did not achieve high savings, considering the low impact of the Brazilian electricity mix. Leme et al. (2014) also determined by a techno-economic analysis that incineration plants face serious economic barriers in Brazil, and it would require that municipal authorities dispose of much higher budgets for waste management.

Among studies addressing theoretical scenarios including separate collection, the work by Reichert and Mendes (2014) stands out. The authors applied LCA methodology as well as economic and social analysis, to compare eight management scenarios (including a reference with approx. 9% recycling) for the city of Porto Alegre. Alternative scenarios included separate collection of dry recyclables and organics in various degrees combined with different approaches to mixed waste treatment, including incineration and MBT based systems (aerobic, anaerobic and with RDF production). Scenarios with high recycling and full treatment of remaining mixed waste by MBT-based systems performed better in most environmental impact categories, while the scenario based on high recycling was most preferable regarding economic and social effects. Another study by Coelho and Lange (2016) compared theoretical scenarios that achieved the PNRS targets for the Brazilian southeast (case of Rio de Janeiro), i.e. reduce the recyclables and organic waste sent to landfill to 50% and 55%, respectively. Three scenarios

focused on mixed waste treatment, such as incineration and MBT (with ferrous metals recovery and RDF for cement production), while four scenarios assumed that diversion happened mostly by separate collection. The scenarios based on high separate collection displayed also the highest environmental benefits, Bernstad Saraiva et al. (2017) addressed organic waste in Rio de Janeiro and determined that similar environmental performance could be achieved if biowaste would be separated at the source or by mechanical means in MBT facilities with AD. Most importantly, this work also aimed at showing the influence between choosing an attributional vs. a consequential LCA modelling framework. This was demonstrated as very important in a Brazilian decision-making context, due to the specific energy system. Finally, the recent study of Ibáñez-Forés et al. (2017) reports the evolution of MSW management and its related environmental impact between 2005 and 2015, in the city of João Pessoa (Northeast Brazil). The city implemented separate collection of recyclables covering approx. 20% of districts. It is possible to determine that in 2015 the covered areas reached a combined recycling rate of 7% (6% from separate collection, 1% by mixed waste materials recovery facility (MRF)), while 93% of waste was directed to a sanitary landfill. Despite the low recycling performance, the study showed that environmental impacts decreased over time, recycling contributing savings in several impact categories.

1.2 Study objectives

Governments and local authorities in developing countries often aim to emulate successful waste management systems in developed (industrialized, high-income) countries, through initiatives (and legislation) typically focused only on technology issues, forgetting socio-economic, cultural and governance aspects, which almost as often results in implementation failures (Campos, 2014; Wilson, Velis, & Rodic, 2013). Most scientific evaluations of waste management follow the same line as shown also for Brazil with studies targeting treatment or theoretical separate collection scenarios. Successful systems in developed countries incur enormously high costs compared to budgets spent in developing countries (Alfaia et al., 2017; Wilson et al., 2013). However, in the former, these high costs are almost always and entirely, covered by household paid waste fees, a situation which is still far from implementation in the latter (at present).

Beyond the urgent enforcement of safe and controlled disposal in Brazil, possible solutions towards wide-spread management of MSW with the aim of resource recovery and recycling have to take offset in local conditions and should apply options that capitalise on possible synergies with other industry sectors. Such solutions could include the implementation

of: (1) simple and intuitive source separation, such as into dry and wet streams, where this is feasible, and (2) bypass public participation by wide implementation of MBTs or mixed waste MRFs, using concepts that combine dry recyclables recovery, RDF production and the separation and treatment of biodegradable waste. The latter can be realized with technical solutions ranging from very basic to advanced (Cimpan, Maul, Jansen, Pretz, & Wenzel, 2015; Münnich, Mahler, & Fricke, 2006). Because no MSW or RDF dedicated WtE facilities exist in Brazil, production of high quality RDF could be prioritized with the objective to substitute fossil fuels in the cement industry. RDF utilization in the cement industry has been shown superior when compared to WtE that produces only power and when background marginal electricity is not carbon intensive (such as Brazil) (Cimpan & Wenzel, 2013). According to IFC (2017) the alternative fuels co-processing or substitution rate in Brazil was only 8.1% in 2014, while in Europe this was 41%, with high variation between countries (highest 65% in Germany) (de Beer, Cihlar, Hensing, & Zabeti, 2017).

The primary objective of the present study was to evaluate and compare from an environmental impact perspective, different system scenarios built around main technological options for the management of MSW in Brazil. System scenarios considered specific conditions, barriers and sector synergies mentioned above, as well as more theoretical situations with implementation of costly and state-of-the-art options (e.g. WtE). The goal of the study is to inform and support decision-making towards policy development and strategy planning concerning MSW management in Brazil.

2 Materials and methods

2.1 LCA methodology

Considering the goal of this work and that MSW management changes can have potentially large effects on other technological and societal systems, the general methodological framework was based on consequential LCA (EC-JRC, 2011). This implies system expansion in the case of multi-functionality and when a change in waste management influences background systems (e.g. substitution of energy in the energy system). Interactions with adjoining systems were modelled (where possible) by use the marginal LCI data (as opposed to average data), which denotes processes and technologies most likely to respond due to market mechanisms (i.e. supply-demand changes for goods/services). The functional unit (FU) was the management (i.e. from generation to final disposal/sinks) of 1 t (t = metric tonne) of MSW. The

reference flow MSW should be understood as daily-generated household waste, street sweepings and similar waste from small business, service and institutions.

The modelling was performed in EASETECH, a software developed in Denmark specifically for waste management LCA (Clavreul, Baumeister, Christensen, & Damgaard, 2014). This software allows detailed mass and substance flow modelling of waste management chains. Life cycle impact assessment (LCIA) was performed with the ILCD recommended method, and included 12 impact categories (listed in Table 1-1). Normalization factors for emissions and resource extraction, geographically representative as global, were based on DTU (2016); and Sala, Crenna, Secchi, and Pant (2017).

Biogenic CO₂ originating from the waste was considered to be climate neutral, while biogenic carbon that was not emitted after 100 years was considered stored (and accounted as an avoided impact) according to the method in Christensen et al. (2009). Nevertheless, due to mostly warm and wet climate conditions characterizing Brazil, carbon storage was deemed insignificant with the application on soil of compost and digestate, and in the cases of semi-controlled and controlled dumps, in accordance with a previous study by Bernstad Saraiva et al. (2017).

Table 1-1 – Normalization factors ILCD recommended.

ILCD Impact Category	Abbreviation	Unit	Normalization factor
Climate change (GWP)	GWP100	kg CO ₂ eq. PE ⁻¹ year ⁻¹	8,400
Ozone depletion	ODP	kg CFC-11 eq. PE ⁻¹ year ⁻¹	0.0234
Human toxicity, cancer effects	HT, CE	CTUh PE ⁻¹ year ⁻¹	3.85E-05
Human toxicity, non-cancer effects	HT, non CE	CTUh PE ⁻¹ year ⁻¹	4.75E-04
Particulate matter	PT	kg PM2.5 eq. PE ⁻¹ year ⁻¹	5.07
Photochemical ozone formation	POF	kg NMVOC eq. PE ⁻¹ year ⁻¹	40.6
Terrestrial Acidification	TAD	mol H ⁺ eq. PE ⁻¹ year ⁻¹	55.5
Eutrophication terrestrial	EPT	mol N eq. PE ⁻¹ year ⁻¹	177
Eutrophication freshwater	EPF	kg P eq. PE ⁻¹ year ⁻¹	0.734
Eutrophication marine	EPM	kg N eq.	28.3
Ecotoxicity freshwater	ECF	CTUe	11,800
Depletion of abiotic resources, mineral, fossils and renewables	DAMR	kg Sb eq.	0.193

2.1.1 Temporal, geographical and technological scope

The results of this assessment can be considered valid short-to-medium term, i.e. 5 to 10 years. Inventory data for foreground systems refer to current treatment technologies and substantial technological changes are not expected within the time frame. Technology performance was based on the data from different published research sources and the EU Best Available Techniques for the Waste Treatment Industries (BREF). The geographical scope refers to Brazil, nevertheless, the origin of many foreground processes was European, adapted to average Brazilian climate conditions, while the origin of some background processes was European or Global averages (e.g. primary materials and fuels production).

2.1.2 System boundaries

The systems in this evaluation should be understood as the sum of a foreground system and background system, using the definitions from Clift et al. (2000) and EC-JRC (2011). In the analysis of waste management systems, the foreground system comprises all waste management activities from waste generation, through treatment and recovery of materials and/or energy, to the point where these functional outputs are exchanged with the background systems (the background economy and markets). The background systems represent the economic activities (e.g. energy production, material production) which exchange materials and energy (including the functional outputs from waste management) with the foreground system and thus affect the decisions taken regarding foreground systems.

2.2 Description of alternative systems (foreground scenarios)

Table 1-2 shows the foreground system scenarios and variations evaluated in this work. Category 2 systems are based on a theoretical (but plausible) separate collection efficiency of 20% (for dry streams), whereas the rest is considered a wet stream. The focus was to highlight the effects of different biological treatment, rather than source separation, which was handled here in a generic way.

Table 1-2– Summary table for the foreground scenarios

Main system category	System scenario	System variation	scenario
1. Mixed waste direct disposal systems	1.a - Semi-controlled dumps		
	1.b - Controlled dumps		
	1.c - Sanitary or fully controlled landfilling without landfill gas valorisation		

Main system category	System scenario	System variation	scenario
	1.d - Sanitary or fully controlled landfilling with landfill gas valorisation		
	1.e- Incineration WtE by means of moving grate combustion		
2. Separate collection systems – source separation into wet and dry streams (80%:20%)	2.a - Dry stream sorted in a simple MRF and wet stream sanitary landfilling	2.c(w) open air composting	
	2.b - Dry stream sorted in an advanced MRF and wet stream sanitary landfilling	2.c(e) enclosed composting	
	2.c - Dry stream sorting and wet stream composting	2.d(u), 2.e(u) biogas upgraded and used as vehicle fuel	
	2.d - Dry stream sorting and wet stream dry digestion, biogas to electricity production		
	2.e - Dry stream sorting and wet stream pre-treatment and wet digestion, biogas to electricity production		
3. Mixed waste mechanical-biological and sorting systems	3.a - Simple Aerobic MBT	3.b(u) biogas upgraded and used as vehicle fuel	
	3.b - Advanced Anaerobic-aerobic MBT (incl. material recovery)		
	3.c - Simple Biological drying MBT		
	3.d - Advanced Biological drying MBT (incl. material recovery)		

Screenshots of each scenario and of some sub processes were taken from EASETECH and they are shown below. Fig. 1-1 shows the template for scenarios 1.a, 1.b, 1.c and 1.d that just changed the names in the last boxes. Fig. 1-2 shows the basic template for the landfills used for scenarios 1. The layout for all of them looked the same with the differences contained in some parameters as described in before. For the WtE scenario the same template for scenarios 1 was applied but with some changes due to the different outputs as shown in Fig. 1-3.

Fig. 1-4 and Fig. 1-5 shows scenarios 2a and 2b respectively. Fig. 1-6 presents the variation in 2c(w) with only the dry stream shown, as the wet stream has the same behaviors of 2a and 2b. Windrows composting template is shown in Fig. 1-7 and it was used the same scheme for the scenarios that considered this treatment for the wet waste, including post-composting for the digestions. The EASETECH processes used for the fertilizer substitution are shown in Fig. 1-8 and the same template was used in other scenarios. For scenarios 3 some parameters were altered for land reclamation, but the template used was the same. All the scenarios that presented enclosed composting as a treatment option has the template shown in Fig. 1-10. For the sensitivity with post-composting as a test parameter this was used as well.

For anaerobic digestions, both wet and dry, the templates are shown in Fig. 1-12 for electricity and heat substitution, and in Fig. 1-14 for fuel upgrading. Fig. 1-11, Fig. 1-13, Fig. 1-15, Fig. 1-16, presents the templates for scenarios 2d and 2e and its variations of biogas upgrading to vehicle fuel.

Category 3 of scenarios are shown from Fig. 1-17 to Fig. 1-23. Being Fig. 1-18 and Fig. 1-22 the templates for RDF combustion to cement production and biodrying respectively.

Fig. 1-1 - Scenario 1.a. Semi-controlled dumps.

Fig. 1-2 - Landfill template.

Fig. 1-3 - Scenario 1.e. Waste-to-Energy (WtE) by means of moving grate combustion.

Fig. 1-4 - Scenario 2.a. Dry stream sorted in a simple MRF and wet stream sanitary landfilling.

Fig. 1-5 - Scenario 2.b. Dry stream sorted in an advanced MRF and wet stream sanitary landfilling.

Fig. 1-6 - Scenario 2.c(w). Open air composting

Fig. 1-7 - Windrows composting template.

Fig. 1-8 - Fertilizer substitution template.

Fig. 1-9 - Scenario 2.c(e). Dry stream sorting and wet stream pre-treatment and wet digestion, biogas to electricity production.

Fig. 1-10 - Enclosed composting template.

Fig. 1-11 - Scenario 2.d. Dry stream sorting and wet stream dry digestion, biogas to electricity production.

Fig. 1-12 – Anaerobic digestion with substitution template.

Fig. 1-13 - Scenario 2.d(u). Biogas upgraded and used as vehicle fuel

Fig. 1-14 - Anaerobic digestion with fuel upgrading template.

Fig. 1-15 - Scenario 2.e. Dry stream sorting and wet stream pre-treatment and wet digestion, biogas to electricity production.

Fig. 1-16 - Scenario 2.e(u). Dry stream sorting and wet stream pre-treatment and wet digestion, biogas upgraded and used as vehicle fuel.

Fig. 1-17 - Scenario 3.a. Simple Aerobic MBT.

Fig. 1-18 - RDF to cement production template.

Fig. 1-19 - Scenario 3.b. Advanced Anaerobic-aerobic MBT.

Fig. 1-20 - Scenario 3.b(u). Biogas upgraded and used as vehicle fuel.

Fig. 1-21 - Scenario 3.c. Simple Biological drying MBT.

Fig. 1-22 - Biodrying template.

Fig. 1-23 - Scenario 3.d. Advanced Biological drying MBT.

2.3 Life cycle inventory (LCI)

2.3.1 MSW generation

An average Brazilian waste composition was established after compiling data from a large number of studies representing the different country regions. The composition was first calculated as a weighted average (based on population) of 15 studies (Colvero, Pfeiffer, & Carvalho, 2016). The data sources mostly consisted of gravimetric analyses performed on municipal waste sampled at the source of generation (households) before intervention from the informal sector. The informal sector is accounted in official sources as capturing 3.6% wt of generated waste (consisting mostly of dry recyclable materials) (SNSA, 2016). In this work, we assumed that in all the systems modelled, the intervention from the informal sector remains constant. Therefore, the initial composition was adjusted to represent the waste after removal of 3.6% materials. The composition before and after (the latter representing the FU of this work) is presented summarized in Table 1-3. The detailed methodology can be found in the APPENDIX A.

Table 1-3 – Waste composition for Brazil.

Waste fraction	Generated before informal sector (kg)	Generated before informal sector (%)	FU after informal sector (kg)	FU after informal sector (%)
Paper	75.8	7.31	60.1	6.01
Cardboard	69.4	6.69	67.9	6.79
Beverage cartons	3.4	0.33	2.7	0.27
Metals	18.2	1.75	11.4	1.14
Glass	25.3	2.44	22.7	2.27
Plastics	185.4	17.87	175.3	17.53
Organic	548.5	52.88	548.5	54.85
Other combustibles	49.9	4.81	49.9	4.99
Other non-combustibles	60.0	5.78	60.0	6.00
Hazardous	1.5	0.14	1.5	0.15
TOTAL	1,037	100	1,000	100

2.3.2 LCI for foreground system processes

Collection and transport: Waste collection accounted for route collection and transport to the first handling facility. Collection was modelled considering a regular (rear-loading) truck and different diesel consumption (in litres of diesel per tonne of collected waste ($L\ t^{-1}$)). Diesel consumption was set to $3.0\ L\ t^{-1}$ for mixed and wet stream collections, while for dry stream collection it was $6.0\ L\ t^{-1}$. The latter considered the potentially higher dispersion of collection

points and lower truck capacity due to higher bulk density. Long-distance transportation was largely based on Bassi et al. (2017) and Vergara et al. (2016) and further considering that the MRFs and MBTs would be located relatively near to landfills (see Table 1-4).

Table 1-4 – Collection and transportation vehicles, travelled distances and fuel consumptions.

Collection and/or waste type	Type of vehicle	Distances (km)	Fuel consumptions (L t ⁻¹)
Mixed waste collection	Collection truck 10 t	-	3.0
Dry stream collection	Collection truck 10 t	-	6.0
Wet stream collection	Collection truck 10 t	-	3.0
Ferrous and non-ferrous metal to recycling	Long haul truck 25 t	350	0.03·distance
Glass to recycling	Long haul truck 25 t	200	0.03·distance
Paper and cardboard to recycling	Long haul truck 25 t	400	0.03·distance
PET, HDPE and LDPE to recycling	Long haul truck 25 t	350	0.03·distance
RDF to cement kilns	Long haul truck 25 t	400	0.03·distance
Residue streams (sorting, ash) to landfill	Collection truck 10 t	5	0.06·distance

Source: (Bassi, Christensen, & Damgaard, 2017b; Sala et al., 2017; Vergara et al., 2016)

Source separation and material recovery facilities (MRFs): Source separation programmes are slowly expanding in Brazil. Where implemented, the model is based on separation into dry-wet streams, which should be convenient and easy to follow for citizens. The dry stream is a mixture of different recyclable materials and miss-sorted non-recyclables (contamination). The materials fraction composition was based on the report from Prefeitura Municipal de Campo Grande (2017). The dry stream has to undergo sorting, which can happen in various conditions. We modelled two contrasting cases: (1) a simple MRF, reflecting small scale, low technology plants (mainly manual sorting) which are common in Brazil, and (2) an advanced MRF, reflecting more the state-of-the-art in Europe and the US, characterized by larger scale and mechanical sorting complemented with manual sorting. Consumption of electricity (15 and 20 kWh.t⁻¹, respectively), diesel (0.7 L.t⁻¹) and steel wire for bales (0.85 kg.t⁻¹) was estimated considering previous work by Cimpan et al. (2016, 2015). Sorting efficiencies in the two plants are presented in the Table 1-5, the first number represents the MRF low tech: low technology, low to medium capacity, manual picking plant and the second number, represented in red colour, the MRF high tech: high technology, medium to large capacity, mechanical sorting and manual picking plant.

Table 1-5 – Transfer coefficients for MRFs low and high tech.

Waste Fractions	Outputs (% transferred)										
	Paper	Cardboard	Fe-metal	Al-metal	Glass	2D	3D - PET	3D - PP	3D - PE	Sorting residues	
Office Paper	90/90									10/10	
Other clean Paper	90/90									10/10	
Juice Cartons		-/80								100/20	
Magazines	90/90									10/10	
Newsprint	90/90									10/10	
Other Clean Cardboard		95/95								5/5	
Food cans (tinplate/steel)			95/95							5/5	
Beverage cans (Aluminium)				95/95						5/5	
Clear Glass					50/80					50/20	
Brown Glass					-/80					100/20	
Soft Plastic						70/80				30/20	
Plastic Bottles							90/90			10/10	
Hard Plastics							-/12	-/26	17/35	83/27	
Non-recyclable Plastic										100/100	
Plastic products										100/100	
Animal Food										100/100	
Vegetable Food										100/100	
Diapers, sanitary towels, tampons										100/100	
Rubber										100/100	
Shoes, leather										100/100	
Other combustibles										100/100	
Textiles										100/100	
Wood residues										100/100	
Other non-combustibles										100/100	
Batteries										100/100	

Source: (Cimpan et al., 2016; Cimpan, Rothmann, Hamelin, & Wenzel, 2015)

Landfilling: In EASETECH, landfilling is modelled with specialized modules which can be combined and adapted by changing a variety of parameters in order to reflect different types of landfills running in different climatic conditions. Brazil has regional climatic differences, but in this work was approximated to a tropical humid and wet climate, considering average annual temperatures above 20°C with average precipitation greater than 1,000 mm.year⁻¹ (ABRELPE, 2013a). Climate conditions influence the decay rate of (biodegradable) waste materials and thus gas (and methane) generation (Olesen & Damgaard, 2014). 1st order decay rates (k) for methane

generation were changed to reflect Brazilian climate conditions. Different types of landfilling practice further alter the k values and the generation of leachate. Thus, a methane correction factor (MCF) was used for each of the three landfill types (semi controlled and controlled dump, and sanitary landfill), based on (ABRELPE, 2013). Regarding the leachate generation, it was considered a 10m height for the layers for all landfills, a waste density of 1 tonne.m^{-3} and 100 years as time horizon (Lagerkvist, Ecke, & Christensen, 2011; Manfredi & Christensen, 2009; Olesen & Damgaard, 2014). The main parameters used are presented in Table 1-6.

Table 1-6 – Landfill parameters used in EASETECH.

Technology	Description	Units	Semi-controlled dump	Controlled dump	Sanitary flare	Sanitary - energy
			No top cover, no gas and leachate collection	Top cover, no gas and leachate collection	Top cover, gas and leachate collection	Top cover, gas and leachate collection
Construction and Operation	Diesel consumption	L t^{-1} waste	2.02E-04	2.02E-04	2.02E-04	2.02E-04
	Electricity consumption	kWh t^{-1} waste	None	None	8.00E-03	8.00E-03
Landfill Gas Generation	Correction factor for decay rate		0.4	0.8	1.0	1.0
LFG - Gas Collected	Year 0 - 5	% of generated	0	30*	45	45
	Year 5 - 15	% of generated	0	45*	80	80
	Year 15 - 55	% of generated	0	55*	95	95
	Year 55 - 100	% of generated	0	0*	0	0
LFG - Treatment	No treatment	% of collected	100	100	0	0
	Fugitive emissions	% of collected	0	0	2	2
	Flare or gas motor	% of collected	0	0	98	98
LFG - Top cover	Oxidation	% CH_4	0	18	36	36
Leachate Generation	Net Infiltration	mm yr^{-1}	1000	900	650	650
Leachate Collection	Year 0 - 80	% of generated	0	0	99.9	99.9
	Year 80 - 100	% of generated	0	0	95	95
Leachate Treatment	Type treatment		None	None	POTW	WWTP
Storage of carbon		% remaining C-biogenic	0	0	100	100

Source: (Lagerkvist et al., 2011; Manfredi & Christensen, 2009; Olesen & Damgaard, 2014)

*In the case of controlled dump these percentages denote gas that bypasses the top cover and is released to air unaffected.

Waste-to-Energy (WtE): or waste incineration was considered as a landfill alternative in the first category of systems (system 1.e). The process was modelled as state-of-the-art grate incineration with wet flue gas cleaning, with data from Danish facilities (Møller, Jensen, Kromann, Neidel, & Jakobsen, 2013). This was adopted due to the assumption that if such a technology would be implemented in Brazil, it would be a very efficient one, most likely imported from a developed country. The plant efficiency was set to a net of 25% for electricity generation, meaning 25% of the thermal energy contained by the waste input (based on lower heating value) and after self-consumption is accounted. Energy content and GHG emissions consider the chemical characteristics of material fractions, based on the model library (Riber et al., 2009). Considering the lack of infrastructure and need for district heating in Brazil, no heat recovery was assumed. Bottom ash, fly ash and air pollution control residues were assumed sent to an inert landfill and recovered iron sent to recycling.

Biological treatment: The wet stream collected after source separation, in the second category of systems evaluated in this study, is still highly contaminated with other materials (30-40% is not biowaste). Before biological treatment, the stream has to undergo at least a simple pre-treatment to concentrate the biodegradable fractions. This was modelled as basic bag opening (coarse shredding) and screening (trommel screen). The process sequence for biological treatment is described in Table 1-7, while a summary of the consumption and emissions parameters used for all the biological treatments are shown in Table 1-9.

Composting: Composting processes were based on datasets available in the EASETECH database. Open windrows composting mass balance, process inputs and emissions were based on Andersen et al. (2010), whereas enclosed windrows/channel composting was based on data from facilities in Italy from EASETECH.

Dry digestion: Dry or high-solids digestion is anaerobic digestion performed with waste having total solids (TS) content between 20% and 50%. Existing technologies are well suited for heterogeneous waste streams and do not require intensive pre-treatment. The process modelled in this study uses gas-proof box-shaped reactors, operated in batch mode at mesophilic temperatures. The biomass intended to be digested is mixed on a 50:50 ratio with substrate that has already been digested (this serves as inoculum) and fed via front-end loader into the reactors. The substrate remains in the digester for a period of approx. 4-5 weeks, however if subsequent digester cycles are considered the total retention time is approx. 8-10 weeks. Once the material is inside the reactors no further mixing is required, however, excess

cell fluid (percolation liquid) discharged during the fermentation process is collected by a drainage system and returned to the digesting material in a cycle to keep it moist. Wall and floor heating are used to keep the temperature of the microorganisms constant.

Wet digestion: Wet digestion systems operate with Total Solids (TS) content less than 15% and typically utilize continuous stirred tank reactors (CSTR), whereby continuous mixing is ensured by mechanical means and/or biogas injection. The process requires a homogenization of the substrate to low particle size, removal of contaminants and addition of moisture to a level that the substrate is pumpable. Therefore an additional pre-treatment was modelled, i.e. pre-treatment by pulping, which is utilized in many biowaste AD facilities in Europe.

Table 1-7– Technology description of biological treatment used in the study.

Technology descriptions	Composting Open	- Composting Enclosed	- Dry anaerobic digestion	Wet anaerobic digestion	Simple aerobic MBT	Advanced anaerobic-aerobic MBT	Simple biological drying MBT	Advanced biological drying MBT
System scenario	2.c(w)	2.c(e)	2.d	2.e	3.a	3.b	3.c	3.d
Input waste flow	Wet stream	Wet stream	Wet stream	Wet stream	Mixed MSW	Mixed MSW	Mixed MSW	Mixed MSW
Pre-treatment Mechanical sorting	/ Bag opening and screening	Bag opening and screening	Bag opening and screening	Bag opening and screening, pulping	Simple pre-conditioning, Fe metals separation	Complex pre-conditioning, sorting of recyclables	Simple pre-conditioning, Fe metals separation	Complex pre-conditioning, sorting of recyclables
Main biological treatment	Open windrows composting	Enclosed windrows/channel composting	Dry AD (batch, mesophilic)	Wet AD (continuous, mesophilic), Digestate liquid-solid separation	Enclosed windrows/channel composting	Dry AD (batch, mesophilic)	Biological drying in liquid-tight box reactors	Biological drying in liquid-tight box reactors, automatic handling
Curing/stabilization	Included in main treatment	Included in main treatment	Open windrows	Open windrows (digestate solid fraction)	Included in main treatment	Enclosed windrows/channel composting	no	no
Post-treatment	Screening	Screening	Screening	no	Screening	Screening	Densimetric separation of inerts	Densimetric separation of inerts
Air treatment	no	Acid scrubber, no biofilter		no	Dedusting, acid scrubber, biofilter	Dedusting, acid scrubber, biofilter	Dedusting, acid scrubber, biofilter	Dedusting, acid scrubber, RTO
Compost application (like)	Agriculture (clay soil)	Agriculture (clay soil)	Agriculture (clay soil)	Agriculture (clay soil)	Land reclamation and landfill cover	Land reclamation and landfill cover	no (inert residue is landfilled)	no (inert residue is landfilled)

Source: (Andersen et al., 2010; Clavreul et al., 2014)

The process has, three main steps: shredding, pulping and separation (screening) (Naroznova, Møller, Larsen, & Scheutz, 2016a). Additional grit removal, floating material removal, and dewatering processes can be used to improve the final quality of the biopulp (organic slurry).

The wet waste that is going to treatment (either composting or digestion) goes through a pre-treatment consisted of a basic bag opening (coarse shredding) and screening (trommel screen). For the wet digestion specifically, the waste has to undergo to another pre-treatment after the screening in order to homogenize the substrate to low particle size, remove contaminants and add moisture to a level that the substrate is pumpable. Therefore, based on Naroznova, Møller, Larsen, et al. (2016) the transfer coefficients presented in Table 1-8 were used for the wet fraction.

Table 1-8 - Transfer coefficients for wet waste pre-treatment and the pulper technology.

Waste Fraction	Screening (%)		Pulper (%)	
	Biowaste	Sorting Residues	Biowaste	Residues
Animal food waste	85	15	97	3
Batteries	10	90	0	100
Beverage cans (aluminium)	50	50	4	96
Brown glass	80	20	31	69
Clear glass	80	20	31	69
Diapers, sanitary towels, tampons	50	50	99	1
Food cans (tinplate/steel)	50	50	2	98
Hard plastic	15	85	0.2	99.8
Juice cartons (carton/plastic/aluminium)	30	70	99	1
Magazines	30	70	99	1
Newsprints	30	70	99	1
Non-recyclable plastic	15	85	0.2	99.8
Office paper	30	70	99	1
Other clean cardboard	30	70	99	1
Other clean paper	30	70	99	1
Other combustibles	10	90	11	89
Other non-combustibles	70	30	35	65
Plastic bottles	15	85	0.2	99.8
Plastic products (toys, hangers, pens)	15	85	0.2	99.8
Rubber	10	90	0	100
Shoes, leather	10	90	0	100

Waste Fraction	Screening (%)		Pulper (%)	
	Biowaste	Sorting Residues	Biowaste	Residues
Soft plastic	15	85	0.2	99.8
Textiles	10	90	3	97
Vegetable food waste	85	15	95	5
Wood	10	90	77	23

Source: (Naroznova, Møller, Larsen, & Scheutz, 2016b)

Emissions from biological treatment: Air emissions (especially GHGs) can vary considerably and are dependent on a variety of factors including the matrix of the waste processed, type of technology (open vs. encapsulated) and applied air treatment techniques. A variety of sources were consulted in order to establish a baseline for air emissions in this study, including (among many more) the BREF (European Commission, 2006), benchmark emissions is UK facilities (DEFRA, 2011), experiments (Germany) and literature (Amlinger, Peyr, & Cuhls, 2008), German MBT facilities (Fricke, Santen, & Wallmann, 2005) and Spanish composting and AD facilities (Colón et al., 2015).

Table 1-9– Parameters adopted for the biological treatment processes (biogas upgrading and combustion not included here).

Process consumptions and direct emissions	Unit	Composting - Open	Composting - Enclosed	Wet anaerobic digestion	Dry anaerobic digestion
Pre-treatment					
Electricity (Mechanical)	kWh t ⁻¹ input	15	15	15	15
Electricity (Pulping)	kWh t ⁻¹ input	-	-	41	-
Water (Pulping)	m ³ t ⁻¹ input	-	-	1.2	-
Main biological treatment					
Electricity	kWh t ⁻¹ input				
Diesel	L t ⁻¹ input	0.2	53	20	30
Heat*	MJ t ⁻¹ input	3	1	0.5	1.5
Stabilization and post-treatment		-	-	60.3	57.6
Electricity	kWh t ⁻¹ input				
Diesel	L t ⁻¹ input				
	% CH ₄ biogas	Included in main treatment	Included in main treatment	50%*(open windrow composting)	50%*(open windrow composting)
Emissions to air					

Process consumptions and direct emissions	Unit	Composting - Open	Composting - Enclosed	Wet anaerobic digestion	Dry anaerobic digestion
CH ₄ AD (fugitive)	% C degraded	n.a.	n.a.	2	2
CH ₄ aerobic treatment	% N degraded	2.24	2.24 (-0.05)	stabilization based on open windrow composting parameters	stabilization based on open windrow composting parameters
N ₂ O	% N degraded	15	1.4		
NH ₃	% N degraded	83	83 (-0.01)		
NMVOCs	kg t ⁻¹ input	2	2 (0.05)		

Source: (Amlinger et al., 2008; Colón et al., 2015; DEFRA, 2011; European Commission, 2006; Fricke et al., 2005)

* only in scenario systems with biogas upgrading (when biogas is used directly for energy production it is assumed that heat needs are covered on site)

The emissions from the biogas upgrading and combustion are presented in Table 1-10.

Table 1-10 – Emissions from combustion of biogas to electricity and heat.

Name	Amount	Unit
Nitrogen oxides	0.000202/CH ₄ _LHV	kg/m ³ CH ₄
NM VOC, non-methane volatile organic compounds, unspecified origin	1E-05/CH ₄ _LHV	kg/m ³ CH ₄
Carbon monoxide, fossil	0.00031/CH ₄ _LHV	kg/m ³ CH ₄
Dinitrogen monoxide	1.6E-06/CH ₄ _LHV	kg/m ³ CH ₄
Ammonia	0/CH ₄ _LHV	kg/m ³ CH ₄
Particulates, > 10 um	2.18E-06/CH ₄ _LHV	kg/m ³ CH ₄
Particulates, > 2.5 um, and < 10um	2.45E-07/CH ₄ _LHV	kg/m ³ CH ₄
Particulates, < 2.5 um	2.06E-07/CH ₄ _LHV	kg/m ³ CH ₄
Arsenic	2E-12/CH ₄ _LHV	kg/m ³ CH ₄
Cadmium	1E-12/CH ₄ _LHV	kg/m ³ CH ₄
Chromium	2E-10/CH ₄ _LHV	kg/m ³ CH ₄
Copper	1.3E-10/CH ₄ _LHV	kg/m ³ CH ₄
Mercury	1.2E-10/CH ₄ _LHV	kg/m ³ CH ₄
Nickel	5E-12/CH ₄ _LHV	kg/m ³ CH ₄
Lead	1.2E-11/CH ₄ _LHV	kg/m ³ CH ₄
Selenium	2E-12/CH ₄ _LHV	kg/m ³ CH ₄
Zinc	4.2E-10/CH ₄ _LHV	kg/m ³ CH ₄
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	9.6E-16/CH ₄ _LHV	kg/m ³ CH ₄
Benzo(b)fluoranthene	1.2E-12/CH ₄ _LHV	kg/m ³ CH ₄
Benzo(a)pyrene	1.3E-12/CH ₄ _LHV	kg/m ³ CH ₄
Methane, non-fossil	0.000434/CH ₄ _LHV	kg/m ³ CH ₄
Fluoranthene	6E-12/CH ₄ _LHV	kg/m ³ CH ₄

Name	Amount	Unit
Benzo(k)fluoranthene	1.2E-12/CH ₄ _LHV	kg/m ³ CH ₄
Benzo(ghi)perylene	1.1E-12/CH ₄ _LHV	kg/m ³ CH ₄
Indeno(1,2,3-cd)pyrene	6E-13/CH ₄ _LHV	kg/m ³ CH ₄
Sulfur dioxide	1.92E-05/CH ₄ _LHV	kg/m ³ CH ₄
Benzene, hexachloro-	1.9E-13/CH ₄ _LHV	kg/m ³ CH ₄

Source: <http://www.air.sk/en/corinair.php>; <http://www2.dmu.dk/Pub/FR795.pdf>, Nielsen, M., Nielsen, O.-K., Plejdrup, M., Hjelgaard, K., 2010. Danish emission inventories for stationary combustion plants - NERI Technical Report no. 795.; http://www.dmu.dk/fileadmin/Resources/DMU/Luft/emission/2012/Emf_internet_januar2013_GHG.htm; http://www.dmu.dk/fileadmin/Resources/DMU/Luft/emission/2012/Emf_internet_januar2013_HM_POP.htm.

Mechanical Biological Treatment: MBT facilities for mixed MSW were modelled as a combination of sorting and biological treatment processes. Variations labelled as “advanced” in this work include materials sorting for recycling, where recovery efficiencies were based on Cimpan et al. (2015). Degradation and emissions generation from biological processes were assumed to follow the same patterns as for treatment of the wet fraction, where the same type of process and air treatment was employed. Emissions for the simple biological drying MBT were assumed similar to enclosed composting, with the difference that the high rate of aeration prevents formation of methane. Emissions for the advanced biological drying MBT were based on the LCI data in Rigamonti et al. (2012), for a facility employing regenerative thermal oxidation (RTO).

For the MBTs it was used different transfer coefficients to the different possible outputs. Therefore, the coefficients used for simple MBT are presented in Table 1-11 and for the advanced MBT in Table 1-12.

Table 1-11 - Transfer coefficients sorting MBT simple.

Waste Fractions	Outputs (% transferred)			
	Fe-metal	RDF	Residues (for landfill)	Wet (Organics)
Office Paper		80		20
Other clean Paper		80		20
Juice Cartons		80		20
Magazines		80		20
Newsprint		80		20
Other Clean Cardboard		80		20
Food cans (tinplate/steel)	80	10		10
Beverage cans (Aluminium)		50		50
Clear Glass		5	15	80
Brown Glass		5	15	80
Plastics				

Waste Fractions		Outputs (% transferred)									Residues	Wet
		Paper	Cardboard	Fe-metal	Al-metal	2D soft	3D PET	- 3D PP	- 3D PE	- RDF		
Plastic products (toys, hangers, pens)										75	10	15
Animal Food										15		85
Vegetable Food										15		85
Diapers, sanitary towels, tampons										50		50
Rubber										90		10
Shoes, leather										90		10
Other combustibles										90		10
Textiles										90		10
Wood										90		10
Other non-combustibles										10	20	70
Batteries										10	70	20

Source: (Cimpan, Rothmann, et al., 2015)

Biological drying: Biological drying or biodrying is a variation of aerobic decomposition (composting) performed in closed reactors, whereby the biological heat produced by microorganisms in the initial stages of decomposition is harnessed and augmented by intense forced aeration which facilitates the fast removal of moisture by convective evaporation (Velis, Longhurst, Drew, Smith, & Pollard, 2009). Many commercial scale technology providers exist. The process runs between 5 and 15 days (batch-wise), depending on the technology provider. In contrast to classical composting processes, which aim at maximum degradation, the objective in biodrying is the fast removal of moisture, with minimum substrate degradation, until biological activity stops (15-20°C), rendering the output material storable for short-term. The substrate is biodried within air- and liquid-tight box reactors. Filling/unloading can be done completely automatically by means of cranes or manually by means of wheel loaders. A summary of the consumption and emissions parameters is presented in Table 1-13.

Table 1-13– Parameters adopted for the MBT processes.

Process consumptions and direct emissions	Unit	Simple aerobic MBT	Advanced anaerobic-aerobic MBT	Simple biological drying MBT	Advanced biological drying MBT
Process consumptions					
Electricity	kWh t ⁻¹ input	70	80	70	90
Diesel	L t ⁻¹ input	2.5	3	2.5	2
Heat*	MJ t ⁻¹ input	-	57.6	-	-
Steel wire	kg t ⁻¹ input	-	0.13	-	0.13
NG	m ³ t ⁻¹ input	-	-	-	2
Emissions to air					
CH ₄ AD (fugitive)	% CH ₄ biogas	n.a.	2	n.a.	n.a.
CH ₄ aerobic treatment	% C degraded	2.24 (·0.05)	stabilization based on enclosed windrow composting parameters	0	0
N ₂ O	% N degraded	1.4	n.a.	1.4	8.6**
NH ₃	% N degraded	83 (·0.01)		83 (·0.01)	8**
NMVOCs	kg t ⁻¹ input	2 (·0.05)	80	2 (·0.05)	7.7**
NO _x	g t ⁻¹ input	-	3	-	70.00
SO _x	g t ⁻¹ input	-	57.6	-	0.15
CO ₂ fossil (from NG combustion)	kg t ⁻¹ input	n.a.	0.13	n.a.	4.00

Source: (Rigamonti et al., 2012)

* only in scenario systems with biogas upgrading (when biogas is used directly for energy production it is assumed that heat needs are produced on site from natural gas)

** the unit is g t⁻¹ input (Rigamonti et al., 2012)

2.3.3 Functional outputs and LCI data for background (affected) processes

The foreground systems modelled in this study result in final recovered material or energy outputs and/or final sinks (i.e. final deposit in ground, emissions to air, water and soil). The former are called functional outputs, because they constitute products that are sold on related markets and can replace alternative supplies of the same function (called avoided or substituted flows). The processes leading to final recovery and the framework used for substitution is presented in the following sections.

Electricity and heat: Electricity for both process consumption and avoided/substituted production was modelled with LCI data for Brazil imported from the ecoinvent database. A simple technology marginal was chosen to represent the current state and short-term development of electricity production in Brazil in accordance with the analysis carried by

Bernstad Saraiva et al. (2017). Bernstad Saraiva et al. (2017) identified natural gas based electricity production (combined cycle) as the most likely technology to respond in the electricity market. A grid loss factor of 3.9% was applied to differentiate consumption (medium voltage) and substitution (high voltage). Heat was only considered when consumed in anaerobic digestion processes, respectively when considering biogas upgrading instead of electricity production in gas motors. In this case, consumption was assumed as produced from natural gas boilers (assumed marginal).

Reprocessing/ recycling and avoided primary production: Recycling and primary production processes were modelled as generic European and global processes since there is no data available from Brazil specifically. The processes were designed according to EASETECH templates, based on Bassi et al. (2017) and Rigamonti et al. (2012). Recycling was defined by process recovery efficiencies (A) and avoided primary production considered market substitution ratios (B), which are shown in Table 1-14 with the respective ecoinvent processes.

Table 1-14 – Recovery efficiencies and market ratio for the recycling processes.

Material	Recovery efficiency	Substitution ratio	Recycling process	Substituted material
Paper	89%	0.83	“Paper (Newspaper and Magazines) to Newspaper, Generic, EU BAT, 2001”	Virgin newspaper, Europe (generic)”
Cardboard and beverage cartons	89%	0.83	“Paper (cardboard and mixed paper) to cardboard, Sweden 2006”	“Virgin cardboard, 1 kg, Europe (generic), 2001”
Steel	90%	1	“Shredding and reprocessing of steel scrap, Sweden, 2007”	“Steel production, converter, unalloyed, RoW” (ecoinvent 3.4)
Aluminium	83.5%	1	“Aluminium scraps to new Al sheets, Sweden, 2015”	“Aluminium, Al (Primary), World average, 2005”
Glass	95%	1	“Glass cullet to new bottles (remelting), Denmark, 1998”	“Packaging glass production, brown, RoW” (ecoinvent 3.4)
Soft plastic	75.5%	0.81	LDPE recycling, based on HDPE	"Polyethylene production, low density, granulate; RoW" (ecoinvent 3.4)
PET	75.5%	0.81	“PET recycling, Europe based on Rigamonti”	"Polyethylene terephthalate production, granulate, amorphous; RoW" (ecoinvent 3.4)
HDPE	75.5%	0.81	“HDPE recycling, Europe, based on Rigamonti”	"Polyethylene production, high density, granulate; RoW" (ecoinvent 3.4)
PP	75.5%	0.81	“Plastic (PP) to granulate, DK, 2000”	"Polypropylene production, granulate; RoW" (ecoinvent 3.4)

Source: (Bassi et al., 2017b; Rigamonti et al., 2012)

Upgrading of biogas and use as vehicle fuel: Biomethane is used widely as vehicle fuel in Europe, replacing Compressed Natural Gas (CNG) or Liquefied Natural Gas (LNG) especially in busses and trucks. The fuel efficiency of biomethane used in internal combustion engines (ICE) is similar to conventional fuels such as gasoline, but is lower than for diesel by 10-15% (Cong, Caro, & Thomsen, 2017; Delgado & Muncrief, 2015). Modelled processes included biogas upgrading by membrane technology (electricity consumption of $0.24 \text{ kWh m}^3(-1)$), biomethane compression and distribution ($0.065 \text{ kWh m}^3(-1)$, 2% methane loss). Use of biomethane was considered to substitute production and utilization of diesel in an equivalent application (large commercial vehicle), considering a substitution factor of 1:0.9 (MJ:MJ). Biomethane vehicle emissions were based on emission inventories for regular CNG (with the exception of fossil CO_2), an assumption supported by studies such as Hakawati et al. (2017).

RDF to cement kilns: RDF combustion in a cement kiln was modelled with the EASETECH process template for WtE, by applying the input specific transfer coefficients to air given in Genon and Brizio (2008). The process avoids the thermal energy equivalent of petroleum coke use, including its production and combustion. Coke combustion emissions were calculated based on the same transfer coefficients (used for RDF) applied to the average coke composition in Genon and Brizio (2008).

Emissions related to fuels in cement kilns can vary substantially and are mainly determined by the composition of the fuel (input specific), but also by process characteristics (incl. flue gas cleaning). Overall, the risk of emissions to the environment is higher than with dedicated WtE plants because of the simpler flue gas cleaning. Nevertheless, existing experience and research points out advantages of RDF when compared to typical fossil fuel used in the industry (Genon & Brizio, 2008; Rahman, Rasul, Khan, & Sharma, 2015). Besides the reduction in fossil CO_2 , co-combustion of RDF with coke, in general, leads to a reduction of NO_x , connected with process characteristics. RDF can contain larger concentrations of heavy metals and therefore can lead to increased transfer to air (especially the ones very volatile) and in the produced clinker, compared to some fossil fuels. However, effects on the produced clinker are at most minimal. In addition, the ash content of alternative fuels is incorporated in the clinker product, thus substituting other mineral inputs to the process (Thomanetz, 2012). Organic micro-pollutants (PCDD/F, PCB and PAH), are not influenced or may be reduced by co-processing of RDF due to the high thermal destruction capacity of the kilns (Genon & Brizio, 2008; Grosso, Dellavedova, Rigamonti, & Scotti, 2016).

Table 1-15 contains the characteristics of petroleum coke and the transfer coefficients used to determine air emissions, based on Genon and Brizio (2008). The last column to the right contains the emissions to air accounted for coke. The same transfer coefficients are taken into the modelled process for RDF combustion, and thus are applied to the specific characteristics of the RDF composition in each scenario, to generate input specific air emissions.

Table 1-15 – Petroleum coke chemical characteristics and transfer coefficients to the air compartment.

Characteristics		Petroleum coke characterization				Emissions to air	
		Minimum	Maximum	Average	Average as mass [kg/kg]	Transfer coefficient [%]	Transfer to air [kg/kg]
LHV	MJ/kg	33		33.00			
C	%	86.00		86.00	0.86000		3.15 (CO ₂)
H	%	3.60		3.60	0.03600		
Cl	%	0.01		0.01	0.00010	3.400%	3.40E-06
S	%	5.00		5.00	0.05000	3.100%	1.55E-03
N	%	2.00		2.00	0.02000		3.60E-04 (NO _x)
Hg	ppm	0.02	0.10	0.06	6.00E-08	40.000%	2.40E-08
Tl	ppm	0.04	3.00	1.52	1.52E-06	0.875%	1.33E-08
Sb	ppm	0.20		0.20	2.00E-07	0.042%	8.40E-11
As	ppm	0.46		0.46	4.60E-07	0.020%	9.20E-11
Cd	ppm	0.10	0.30	0.20	2.00E-07	1.873%	3.75E-09
Cu	ppm					0.040%	
Sn	ppm					0.043%	
Mn	ppm					0.010%	
Co	ppm					0.014%	
V	ppm	400.00	2342.00	1371.00	1.37E-03	0.050%	6.86E-07
Cr	ppm	2.00	104.00	53.00	5.30E-05	0.018%	9.54E-09
Pb	ppm	2.40	100.00	51.20	5.12E-05	1.015%	5.20E-07
Ni	ppm	200.00	300.00	250.00	2.50E-04	0.019%	4.75E-08
Zn	ppm	6.80		6.80	6.80E-06	0.437%	2.97E-08

Source: (Genon & Brizio, 2008)

2.4 Sensitivity Analysis

Uncertainties with regard to overall technology options applied in the system scenarios was tackled to some extent by modelling technologies that could cover a large interval in environmental impacts, hence the large number of system variations (e.g. open and enclosed biological treatment). Nevertheless, many parameters used in this study suffer from large uncertainty and variability, but due to lack of data from many of the processes in a Brazilian context, measuring uncertainty is a near impossible endeavour. In this work, we instead tested

the sensitivity of baseline results to the variation of a number of important parameters, namely: carbon storage for landfills, electricity marginal and RDF-coke substitution ratios. Furthermore, scenario variations that contained AD were tested by replacing baseline open post-composting with enclosed post-composting. The summary of the performed sensitivity is shown in Table 1-16.

Table 1-16– Parameters and description of the sensitivity analysis performed.

Sensitivity	Variation description	Scenarios where applied
Carbon storage in sanitary landfills	Remaining C after 100 years was set to 0%	1. c and 1.d
Electricity marginal	Replaced by the Brazilian production mix	1.d, 1.e, 2.d and 2.e
RDF-coke substitution ratios	Changed from 1:1 to 1:0.9 (energy content based)	3.a, 3.b, 3.c and 3.d
Post-composting of digestate after anaerobic digestion	Changed from open to enclosed processes	2.d, 2.d(u), 2.e and 2.e(u)

The sensitivity performed for electricity was based on the mix presented in Table 1-17 with the correspondent ecoinvent processes used.

Table 1-17- Electricity mix and ecoinvent processes used for the sensitivity analysis.

Source	Fraction of Production	Ecoinvent Process
Hydropower	64.1%	“electricity production, hydro, run-of-river; RoW”
Biomass	5.7%	“ethanol production from sugar cane; BR”
Wind	5.4%	“electricity production, hydro, run-of-river; RoW”
Import (mostly hydropower)	6.6%	“electricity, high voltage, import from AR; BR”
Nuclear power	2.6%	“electricity production, natural gas, combined cycle power plant;BR”
Natural Gas	11.0%	“electricity production, natural gas, combined cycle power plant;BR”
Coal	4.6%	“electricity production, hard coal; BR”

Source: (MME, 2017)

3 Results

The LCA results are presented in the following sections, as normalized values in mili Person Equivalents (mPE), which allows the comparison between the impact categories. Following an overall comparison of systems, we elaborate by a process contribution analysis

and results of the sensitivity analysis. Furthermore, the characterized results can be verified in the tables below by scenarios group and the most relevant processes (or group of it).

Table 1-18 - Characterized LCA results for scenarios 1.

Category	Scenario	Collection	Construction and operation	LF	LF Gas	Leachate	Carbon storage	Energy savings	WtE	Landfill	Recycling
GWP 100	1.a	9.07	0.73		1222.17	1.79E-03					
	1.b	9.07	0.73		1102.25	1.77E-03					
	1.c	9.07	4.82		450.28	0.97	-208.71				
	1.d	9.07	4.82		442.42	0.97	-208.71	-40.78			
	1.e	9.07						-265.00	480.65	0.94	-11.81
ODP	1.a	3.32E-09	2.64E-10	9.04E-04	0						
	1.b	3.32E-09	2.64E-10	8.70E-04	0						
	1.c	3.32E-09	1.32E-07	3.63E-04	6.76E-08	0					
	1.d	3.32E-09	1.32E-07	3.52E-04	6.76E-08	0		3.62E-05			
	1.e	3.32E-09						-1.84E-05	3.01E-07	3.85E-07	-5.35E-07
HT, CE	1.a	1.24E-08	3.37E-10	4.69E-09	1.45E-06						
	1.b	1.24E-08	3.37E-10	4.46E-09	1.43E-06						
	1.c	1.24E-08	3.19E-08	7.81E-09	2.91E-07	0					
	1.d	1.24E-08	3.19E-08	1.82E-09	2.91E-07	0		-8.41E-08			
	1.e	1.24E-08						-5.12E-07	1.15E-07	3.78E-08	-2.48E-07
HT, non CE	1.a	1.82E-06	1.45E-07	1.36E-07	1.11E-05						
	1.b	1.82E-06	1.45E-07	1.40E-07	1.10E-05						
	1.c	1.82E-06	2.00E-07	1.29E-07	6.51E-06	0					
	1.d	1.82E-06	2.00E-07	5.62E-08	6.51E-06	0		-8.14E-07			
	1.e	1.82E-06						-4.81E-06	8.64E-06	8.10E-07	1.22E-06
PT	1.a	0.01	2.00E-04	0	0						
	1.b	0.01	2.00E-04	0	0						
	1.c	0.01	8.78E-04	2.00E-03	4.79E-05	0					
	1.d	0.01	8.78E-04	0	4.79E-05	0		3.50E-03			
	1.e	0.01						-0.01	0.01	1.71E-04	-0.01
POF	1.a	0.08	0.01	0.58	0						
	1.b	0.08	0.01	0.52	0						
	1.c	0.08	0.01	0.26	1.01E-03	0					
	1.d	0.08	0.01	0.21	1.01E-03	0		0.37			
	1.e	0.08						-0.27	0.88	2.54E-03	-0.01
TAD	1.a	0.07	0.01	0	0						
	1.b	0.07	0.01	0	0						
	1.c	0.07	0.02	0.05	9.22E-04	0					
	1.d	0.07	0.02	0	9.22E-04	0		0.27			
	1.e	0.07						-0.25	0.68	2.70E-03	0.05
EPT	1.a	0.33	0.03	0	0						
	1.b	0.33	0.03	0	0						

Category	Scenario	Collection	Construction and operation LF	LF Gas	Leachate	Carbon storage	Energy savings	WtE	Landfill	Recycling
	1.c	0.33	0.04	0.19	2.41E-03	0				
	1.d	0.33	0.04	0	2.41E-03	0	1.58			
	1.e	0.33					-0.66	3.72	0.01	0.02
EPF	1.a	7.89E-06	6.27E-07	0	1.85E-03					
	1.b	7.89E-06	6.27E-07	0	1.84E-03					
	1.c	7.89E-06	1.87E-06	0	1.44E-03	0				
	1.d	7.89E-06	1.87E-06	0	1.44E-03	0	-9.64E-05			
	1.e	7.89E-06					-5.23E-04	5.53E-06	1.70E-04	-3.47E-04
EPM	1.a	0.03	2.29E-03	0	1.33					
	1.b	0.03	2.29E-03	0	1.32					
	1.c	0.03	3.47E-03	0.02	0.03	0				
	1.d	0.03	3.47E-03	0	0.03	0	0.14			
	1.e	0.03					-0.06	0.34	4.69E-03	3.03E-03
ECF	1.a	1.03	0.08	0.01	247.31					
	1.b	1.03	0.08	0.01	245.33					
	1.c	1.03	0.60	0.02	85.93	0				
	1.d	1.03	0.60	3.30E-03	85.93	0	-17.93			
	1.e	1.03					-97.23	0.92	10.25	-2.98
DAMR	1.a	8.16E-06	6.49E-07	0	0					
	1.b	8.16E-06	6.49E-07	0	0					
	1.c	8.16E-06	1.65E-06	0	2.19E-07	0				
	1.d	8.16E-06	1.65E-06	0	2.19E-07	0	-1.10E-05			
	1.e	8.16E-06					-5.97E-05	1.37E-05	2.76E-07	-3.30E-04

Table 1-19 - Characterized LCA results for scenarios 2.

Category	Scenario	Collection	MRF	Recycling	Landfill	Pre-treatment operation	Composting operation	Composting emissions	Avoided fertilizer	Digestion operation	Digestion emissions	Post-composting	Avoided energy	Fuel substitution
GWP	2.a	10.89	2.16		214.75									
	2.b	10.89	2.56		216.48									
	2.c(w)	10.89	2.56	-104.26	20.77	4.80	4.84	205.76	-8.60					
	2.c(e)	10.89	2.56	-104.26	20.77	4.80	12.79	17.97	-8.63					
	2.d	10.89	2.56	-104.26	-3.35	4.80			-20.04	8.74	0.21	188.34	-52.32	
	2.d(u)	10.89	2.56	-104.26	-3.35	4.80			-20.04	9.35	0.21	188.34		-99.64
	2.e	10.89	2.56	-104.26	0.34	17.39			-19.32	8.75	0.23	172.84	-55.54	
	2.e(u)	10.89	2.56	-104.26	0.34	17.39			-19.32	9.86	0.23	172.84		-105.73
ODP	2.a	3.99E-09	1.09E-07		3.54E-04									
	2.b	3.99E-09	1.37E-07		3.54E-04									
	2.c(w)	3.99E-09	1.37E-07	-4.85E-05	8.75E-05	3.33E-07	4.69E-09	0	2.63E-11					
	2.c(e)	3.99E-09	1.37E-07	-4.87E-05	8.75E-05	3.33E-07	7.78E-07	0	1.85E-11					
	2.d	3.99E-09	1.37E-07	-4.87E-05	7.45E-05	3.33E-07			4.35E-11	4.41E-07	0	2.08E-09	-3.63E-06	
	2.d(u)	3.99E-09	1.37E-07	-4.87E-05	7.45E-05	3.33E-07			4.35E-11	4.42E-07	0	2.08E-09		-1.69E-05
	2.e	3.99E-09	1.37E-07	-4.87E-05	1.77E-05	9.57E-07			3.98E-11	5.11E-07	0	1.09E-09	-3.86E-06	
	2.e(u)	3.99E-09	1.37E-07	-4.87E-05	1.77E-05	9.57E-07			3.98E-11	5.13E-07	0	1.09E-09		-1.80E-05
HT, CE	2.a	1.49E-08	2.75E-08		1.96E-07									
	2.b	1.49E-08	2.83E-08		1.93E-07									
	2.c(w)	1.49E-08	2.83E-08	-9.37E-07	1.03E-07	9.26E-09	6.25E-09	0	-4.28E-06					
	2.c(e)	1.49E-08	2.83E-08	-9.65E-07	1.03E-07	9.26E-09	2.37E-08	0	-4.28E-06					
	2.d	1.49E-08	2.83E-08	-9.65E-07	1.04E-07	9.26E-09			-4.28E-06	1.33E-08	0	2.77E-09	-1.01E-07	
	2.d(u)	1.49E-08	2.83E-08	-9.65E-07	1.04E-07	9.26E-09			-4.28E-06	1.36E-08	0	2.77E-09		-2.20E-07
	2.e	1.49E-08	2.83E-08	-9.65E-07	2.65E-08	1.98E-08			-5.16E-06	1.48E-08	0	1.46E-09	-1.07E-07	
	2.e(u)	1.49E-08	2.83E-08	-9.65E-07	2.65E-08	1.98E-08			-5.16E-06	1.54E-08	0	1.46E-09		-2.34E-07

Category	Scenario	Collection	MRF	Recycling	Landfill	Pre-treatment operation	Composting operation	Composting emissions	Avoided fertilizer	Digestion operation	Digestion emissions	Post-composting	Avoided energy	Fuel substitution
	2.b	0.08	2.94E-03		0.25									
	2.c(w)	0.08	2.94E-03	-0.48	0.02	4.54E-03	0.03	7.69	-0.01					
	2.c(e)	0.08	2.94E-03	-0.48	0.02	4.54E-03	0.02	0.08	-0.01					
	2.d	0.08	2.94E-03	-0.48	0.02	4.54E-03			0.19	0.02	0	7.70	-0.05	
	2.d(u)	0.08	2.94E-03	-0.48	0.02	4.54E-03			0.19	0.02	0	7.70		-0.44
	2.e	0.08	2.94E-03	-0.48	0.00	0.06			0.19	0.02	0	7.18	-0.05	
	2.e(u)	0.08	2.94E-03	-0.48	0.00	0.06			0.19	0.02	0	7.18		-0.47
EPT	2.a	0.40	0.02		1.41									
	2.b	0.40	0.02		1.43									
	2.c(w)	0.40	0.02	-0.90	0.07	0.01	0.16	34.28	0.04					
	2.c(e)	0.40	0.02	-0.92	0.07	0.01	0.08	0.34	0.04					
	2.d	0.40	0.02	-0.92	0.07	0.01			0.95	0.10	0	34.35	-0.13	
	2.d(u)	0.40	0.02	-0.92	0.07	0.01			0.95	0.10	0	34.35		-1.47
	2.e	0.40	0.02	-0.92	0.01	0.06			0.91	0.07	0	32.03	-0.14	
	2.e(u)	0.40	0.02	-0.92	0.01	0.06			0.91	0.07	0	32.03		-1.56
EPF	2.a	9.47E-06	1.77E-05		1.20E-03									
	2.b	9.47E-06	1.84E-05		1.18E-03									
	2.c(w)	9.47E-06	1.84E-05	-2.81E-04	4.81E-04	9.46E-06	4.25E-06	0	-0.02					
	2.c(e)	9.47E-06	1.84E-05	-2.99E-04	4.81E-04	9.46E-06	2.35E-05	0	-0.02					
	2.d	9.47E-06	1.84E-05	-2.99E-04	4.87E-04	9.46E-06			-0.02	1.46E-05	0	1.88E-06	-1.03E-04	
	2.d(u)	9.47E-06	1.84E-05	-2.99E-04	4.87E-04	9.46E-06			-0.02	1.48E-05	0	1.88E-06		-2.34E-03
	2.e	9.47E-06	1.84E-05	-2.99E-04	1.25E-04	1.01E-05			-0.02	1.57E-05	0	9.91E-07	-1.10E-04	
	2.e(u)	9.47E-06	1.84E-05	-2.99E-04	1.25E-04	1.01E-05			-0.02	1.62E-05	0	9.91E-07		-2.49E-03
EPM	2.a	0.04	1.49E-03		0.16									
	2.b	0.04	1.59E-03		0.16									
	2.c(w)	0.04	1.59E-03	-0.07	0.02	1.10E-03	0.01	0.23	0.10					
	2.c(e)	0.04	1.59E-03	-0.08	0.02	1.10E-03	0.01	2.34E-03	0.10					

Category	Scenario	Collection	MRF	Recycling	Landfill	Pre-treatment operation	Composting operation	Composting emissions	Avoided fertilizer	Digestion operation	Digestion emissions	Post-composting	Avoided energy	Fuel substitution
	2.d	0.04	1.59E-03	-0.08	0.02	1.10E-03			0.28	0.01	0	0.24	-0.01	
	2.d(u)	0.04	1.59E-03	-0.08	0.02	1.10E-03			0.28	0.01	0	0.24		-0.14
	2.e	0.04	1.59E-03	-0.08	4.27E-03	0.01			0.26	0.01	0	0.22	-0.01	
	2.e(u)	0.04	1.59E-03	-0.08	4.27E-03	0.01			0.26	0.01	0	0.22		-0.15
ECF	2.a	1.24	0.81		61.57									
	2.b	1.24	0.95		60.30									
	2.c(w)	1.24	0.95	-34.11	28.93	1.76	0.52	0	109.06					
	2.c(e)	1.24	0.95	-35.06	28.93	1.76	4.28	0	109.05					
	2.d	1.24	0.95	-35.06	29.31	1.76			109.06	2.57	0	0.23	-19.20	
	2.d(u)	1.24	0.95	-35.06	29.31	1.76			109.06	2.57	0	0.23		-13.68
	2.e	1.24	0.95	-35.06	7.53	2.42			40.27	2.84	0	0.12	-20.38	
	2.e(u)	1.24	0.95	-35.06	7.53	2.42			40.27	2.85	0	0.12		-14.51
DAMR	2.a	9.79E-06	3.63E-05		-8.23E-06									
	2.b	9.79E-06	3.64E-05		-7.59E-06									
	2.c(w)	9.79E-06	3.64E-05	-1.92E-03	7.40E-07	1.08E-06	4.32E-06	0	-2.65E-05					
	2.c(e)	9.79E-06	3.64E-05	-1.96E-03	7.40E-07	1.08E-06	3.96E-06	0	-2.65E-05					
	2.d	9.79E-06	3.64E-05	-1.96E-03	7.37E-07	1.08E-06			-2.65E-05	3.58E-06	0	1.91E-06	-1.18E-05	
	2.d(u)	9.79E-06	3.64E-05	-1.96E-03	7.37E-07	1.08E-06			-2.65E-05	3.78E-06	0	1.91E-06		-2.40E-04
	2.e	9.79E-06	3.64E-05	-1.96E-03	1.87E-07	1.10E-05			-2.54E-05	2.90E-06	0	1.01E-06	-1.25E-05	
	2.e(u)	9.79E-06	3.64E-05	-1.96E-03	1.87E-07	1.10E-05			-2.54E-05	3.27E-06	0	1.01E-06		-2.55E-04

Table 1-20 - Characterized LCA results for scenarios 3.

Category	Scenario	Collection	MBT operation	MBT emissions	Land reclamation	Recycling	Landfill	RDF burning	Avoided coke	Digestion emissions	Avoided energy	Post composting	Fuel upgrading
GWP 100	3.a	9.07	35.52	20.48	16.12	-18.02	9.68	403.79	-794.15				
	3.b	9.07	41.44		11.66	-143.42	-17.95	159.53	-384.05	0.23	-53.57	19.47	
	3.b(u)	9.07	41.44		11.66	-143.42	-17.95	159.53	-384.05	0.22		19.47	-103.54

Category	Scenario	Collection	MBT operation	MBT emissions	Land reclamation	Recycling	Landfill	RDF burning	Avoided coke	Digestion emissions	Avoided energy	Post composting	Fuel upgrading
	3.c	9.07	35.52	12.62		-18.02	3.96	460.18	-937.44				
	3.d	9.07	42.41	2.57		-143.42	3.99	215.40	-537.70				
ODP	3.a	3.32E-09	1.95E-06	0.00E+00	5.18E-11	-8.17E-07	2.41E-05	5.07E-09	-1.13E-04				
	3.b	3.32E-09	2.24E-06		6.77E-11	-5.11E-05	8.95E-06	3.25E-09	-5.46E-05	0	-2.12E-06	0	
	3.b(u)	3.32E-09	2.24E-06		6.77E-11	-5.11E-05	8.95E-06	3.25E-09	-5.46E-05	0		0	-1.76E-05
	3.c	3.32E-09	1.95E-06	0		-8.17E-07	2.99E-06	6.05E-09	-1.33E-04				
	3.d	3.32E-09	2.52E-06	0		-5.11E-05	2.99E-06	4.04E-09	-7.65E-05				
HT, CE	3.a	1.24E-08	6.37E-08	0	2.61E-06	-3.79E-07	3.91E-08	4.59E-07	-1.42E-06				
	3.b	1.24E-08	9.23E-08		2.61E-06	-1.53E-06	4.00E-08	4.34E-07	-6.86E-07	1.20E-12	-3.73E-08	0	
	3.b(u)	1.24E-08	9.23E-08		2.61E-06	-1.53E-06	4.00E-08	4.34E-07	-6.86E-07	0		0	-2.29E-07
	3.c	1.24E-08	6.37E-08	0		-3.79E-07	2.78E-08	4.80E-07	-1.68E-06				
	3.d	1.24E-08	9.61E-08	0		-1.53E-06	2.95E-08	4.55E-07	-9.61E-07				
HT, non CE	3.a	1.82E-06	1.99E-06	0	7.05E-06	1.86E-06	8.31E-07	6.80E-05	-1.59E-05				
	3.b	1.82E-06	2.35E-06		7.06E-06	1.86E-07	8.55E-07	6.32E-05	-7.71E-06	9.68E-11	-7.06E-07	0	
	3.b(u)	1.82E-06	2.35E-06		7.06E-06	1.86E-07	8.55E-07	6.32E-05	-7.71E-06	0		0	-4.03E-06
	3.c	1.82E-06	1.99E-06	0		1.86E-06	6.35E-07	7.27E-05	-1.88E-05				
	3.d	1.82E-06	1.83E-06	0		1.86E-07	6.31E-07	6.78E-05	-1.08E-05				
PT	3.a	0.01	2.75E-03	1.95E-03	1.30E-03	-0.02	3.48E-04	4.06E-03	-0.15				
	3.b	0.01	3.55E-03		0.01	-0.09	2.43E-04	2.61E-03	-0.07	2.72E-06	-0.01	1.95E-03	
	3.b(u)	0.01	3.55E-03		0.01	-0.09	2.43E-04	2.61E-03	-0.07	0		1.95E-03	-4.03E-06
	3.c	0.01	2.75E-03	1.15E-03		-0.02	1.40E-04	4.84E-03	-0.18				
	3.d	0.01	3.18E-03	1.05E-03		-0.09	1.47E-04	3.23E-03	-0.10				
POF	3.a	0.08	0.09	0.06	1.14E-03	-0.02	0.02	0.11	-0.95				
	3.b	0.08	0.10		1.58E-03	-0.55	0.01	0.07	-0.46	3.11E-04	-0.06	1.06	
	3.b(u)	0.08	0.10		1.58E-03	-0.55	0.01	0.07	-0.46	1.01E-04		1.06	-0.81
	3.c	0.08	0.09	0.20		-0.02	3.77E-03	0.13	-1.13				
	3.d	0.08	0.08	0.08		-0.55	3.92E-03	0.09	-0.65				
TAD	3.a	0.07	0.08	0.09	0.06	0.07	0.01	0.09	-2.54				
	3.b	0.07	0.09		0.27	-0.55	4.42E-03	0.06	-1.23	1.58E-04	-0.18	0.09	

Category	Scenario	Collection	MBT operation	MBT emissions	Land reclamation	Recycling	Landfill	RDF burning	Avoided coke	Digestion emissions	Avoided energy	Post composting	Fuel upgrading
	3.b(u)	0.07	0.09		0.27	-0.55	4.42E-03	0.06	-1.23	0		0.09	-0.46
	3.c	0.07	0.08	0.05		0.07	2.33E-03	0.10	-3.00				
	3.d	0.07	0.07	0.08		-0.55	2.46E-03	0.07	-1.72				
EPT	3.a	0.33	0.32	0.39	0.26	0.04	0.02	0.43	-2.04				
	3.b	0.33	0.38		1.20	-1.02	0.01	0.28	-0.99	7.79E-04	-0.13	0.39	
	3.b(u)	0.33	0.38		1.20	-1.02	0.01	0.28	-0.99	0		0.39	-1.52
	3.c	0.33	0.32	0.23		0.04	0.01	0.52	-2.41				
	3.d	0.33	0.29	0.41		-1.02	0.01	0.35	-1.38				
EPF	3.a	7.89E-06	6.17E-05	0	3.45E-03	-5.29E-04	1.72E-04	1.20E-05	-2.81E-03				
	3.b	7.89E-06	8.23E-05		3.45E-03	1.23E-03	1.79E-04	7.73E-06	-1.36E-03	0	-8.23E-06	0	
	3.b(u)	7.89E-06	8.23E-05		3.45E-03	1.23E-03	1.79E-04	7.73E-06	-1.36E-03	0		0	-2.43E-03
	3.c	7.89E-06	6.17E-05			-5.29E-04	1.33E-04	1.44E-05	-3.32E-03				
	3.d	7.89E-06	8.76E-05			1.23E-03	1.32E-04	9.58E-06	-1.90E-03				
EPM	3.a	0.03	0.03	2.69E-03	0.28	4.63E-03	0.01	0.04	-0.19				
	3.b	0.03	0.03		0.45	-0.09	0.01	0.02	-0.09	7.11E-05	-0.01	2.69E-03	
	3.b(u)	0.03	0.03		0.45	-0.09	0.01	0.02	-0.09	0		2.69E-03	-0.14
	3.c	0.03	0.03	1.58E-03		4.63E-03	3.76E-03	0.05	-0.22				
	3.d	0.03	0.03	0.03		-0.09	3.76E-03	0.03	-0.13				
ECF	3.a	1.03	11.06	0	290.38	-4.54	10.35	14.03	-93.40				
	3.b	1.03	12.94		290.04	-59.46	10.75	12.16	-45.17	1.44E-05	-8.61	0	
	3.b(u)	1.03	12.94		290.04	-59.46	10.75	12.16	-45.17	0		0	-14.21
	3.c	1.03	11.06	0		-4.54	8.01	16.73	-110.25				
	3.d	1.03	14.08	0		-59.46	7.96	14.80	-63.24				
DAMR	3.a	8.16E-06	1.31E-05	0	1.27E-07	-5.04E-04	3.05E-07	1.25E-05	-3.85E-04				
	3.b	8.16E-06	4.26E-05		1.66E-07	-1.78E-03	2.99E-07	7.99E-06	-1.86E-04	0	-3.55E-09	0	
	3.b(u)	8.16E-06	4.26E-05		1.66E-07	-1.78E-03	2.99E-07	7.99E-06	-1.86E-04	0		0	-2.49E-04
	3.c	8.16E-06	1.31E-05	0		-5.04E-04	1.86E-07	1.48E-05	-4.55E-04				
	3.d	8.16E-06	4.08E-05	0		-1.78E-03	2.17E-07	9.91E-06	-2.61E-04				

3.1 Overall comparison of systems and impact categories

Table 1-21 shows the normalized net result for each impact category for all system variations, with green and red highlights representing best and worst performing variations. The net represents the sum of environmental burdens and benefits, and thus a positive net denotes an overall impact while a negative one a net saving within an impact category.

At a first glance, it can be observed that the first category, i.e. disposal systems, and in particular 1.a semi-controlled and 1.b controlled dumping, which represent a significant part of current management in Brazil had the highest impact in several categories, including global warming (GWP), ozone depletion (ODP), human toxicity, cancer effects (HT, CE), marine eutrophication (EPM) and freshwater ecotoxicity (ECF). It is important to note that the implementation of some controls, mainly landfill covers, in 1.b can be credited only marginal effects towards mitigating impacts. Concurrently, category three, i.e. mechanical-biological systems showed the highest overall savings in GWP, ODP, particulate matter (PT), photochemical ozone formation (POF), terrestrial acidification (TAD), terrestrial eutrophication (EPT) and ECF. Category two, i.e. systems based on wet-dry separate collection, displayed highly mixed results. Systems that included composting or dry/wet digestion of wet waste had high savings in HT, CE, and freshwater eutrophication (EPF). The same systems showed high impacts in non-cancer effects (HT, non CE). The system variations which included open composting technologies, including after prior digestion of the wet stream (i.e. 2.c(w), 2.d, 2.d(u), 2.e and 2.e(u)), displayed particularly high impacts in PT, POF, TAD and EPT. These impacts seemed mitigated with enclosed composting, i.e. in 2.c(e). All category two systems contributed savings in depletion of abiotic resources, mineral fossil and renewable (DAMR), although category three systems based on advanced (recovery) models showed similar results. Surprisingly, category two systems based on digestion of the wet stream did not have GWP savings and performed similar to variants with composting or sanitary landfilling of the wet stream.

Table 1-21– Normalized net results in mili Person Equivalents (mPE) for Climate Change (GWP), Ozone Depletion (ODP), Human Toxicity, Cancer Effects (HT, CE), Human Toxicity, non-Cancer Effects (HT, non CE), Particulate Matter (PT), Photochemical Ozone Formation (POF), Terrestrial Acidification (TAD), Eutrophication Terrestrial (EPT), Eutrophication Freshwater (EPF), Eutrophication Marine (EPM), Ecotoxicity Freshwater (ECF) and Depletion of Abiotic resources, Mineral fossil and Renewable (DAMR).

	Cat. 1 – Mixed waste disposal systems					Cat. 2 – Wet-dry separate collection systems								Cat. 3 – Mechanical –biological systems				
	1.a	1.b	1.c	1.d	1.e	2.a	2.b	2.c(w)	2.c(e)	2.d	2.d(u)	2.e	2.e(u)	3.a	3.b	3.b(u)	3.c	3.d
GWP	146.7	132.4	30.5	24.7	25.5	16.2	15.0	18.3	-4.9	6.3	0.7	4.8	0.0	-37.8	-42.6	-48.5	-51.7	-48.5
ODP	38.6	37.2	15.5	16.6	-0.8	13.1	13.0	1.7	1.7	1.0	0.4	-1.4	-2.0	-3.7	-4.1	-4.8	-5.5	-5.2
HT, CE	38.0	37.7	8.9	6.6	-15.4	-14.2	-18.9	-131.4	-131.6	-134.4	-137.5	-159.2	-162.5	36.0	24.2	19.3	-38.2	-49.3
HT, non CE	27.8	27.6	18.2	16.4	16.2	12.9	10.8	1025.9	1024.8	1023.9	1017.8	457.6	451.1	138.1	141.2	134.2	126.7	129.5
PT	1.5	1.5	2.0	2.3	-1.7	-8.3	-11.0	22.0	-11.3	22.3	12.9	20.3	10.3	-30.1	-29.0	-27.2	-35.9	-34.4
POF	16.4	15.0	8.8	16.7	16.6	8.2	7.0	22.4	-3.1	17.7	-0.2	5.6	-13.3	-15.2	6.1	-12.3	-15.9	-21.2
TAD	1.3	1.3	2.5	6.4	9.7	-1.2	-2.7	132.1	-5.2	134.9	127.8	125.9	118.4	-37.6	-25.0	-30.0	-47.3	-35.7
EPT	2.0	2.0	3.2	11.0	19.4	5.9	5.3	192.6	0.3	196.9	189.3	183.3	175.3	-1.4	2.6	-5.3	-5.5	-5.8
EPF	2.5	2.5	2.0	1.8	-0.9	2.0	1.2	-25.9	-25.9	-26.0	-29.1	-25.5	-28.7	0.5	4.9	1.6	-4.9	-0.6
EPM	48.0	47.7	3.0	7.5	11.2	4.6	4.3	11.9	3.4	17.5	13.0	16.0	11.3	7.2	12.7	8.1	-3.7	-3.5
ECF	21.1	20.9	7.4	5.9	-7.5	3.2	2.3	9.2	9.4	7.7	8.2	0.0	0.5	19.4	18.1	17.6	-6.6	-7.2
DAMR	0.0	0.0	0.1	0.0	-1.9	-7.6	-10.0	-9.8	-10.0	-10.1	-11.3	-10.0	-11.3	-4.4	-9.9	-11.2	-4.8	-10.3

3.2 Process contribution analysis

Process contributions are illustrated with Fig. 1-24, 25 and 26. Bars above and below the X axis denote burdens and savings, respectively.

3.2.1 Systems based on direct disposal of mixed waste (category 1)

Fig. 1-24 illustrated process contributions to category 1 systems, in which it is clear that improper landfilling (scenarios 1.a and 1.b, semi-controlled and controlled dumps respectively) has a high burden in many impact categories. The biggest contributors for these high impacts are landfill gases (in GWP and ODP) and untreated leachate (in HT, CE, HT, non CE, EPM and ECF). Fully controlled sanitary landfilling reduced the GWP in scenario 1.c by roughly 5 times compared to 1.a, from 1,232 to 256 kg CO₂ eq. per ton of waste, as well as the high impact of untreated leachate in several categories. Landfill gas utilization for the production of electricity in 1.d had a beneficial effect on GWP, HT (both cancer and non-cancer) and ECF, but it contributed burdens in ODP, PT, POF, TAD, EPT and EPM. This was connected mainly to emissions of nitrogen oxides (NO_x) and CFCs in the combustion process (gas motors). In our model, the process for flaring had a higher efficiency in destruction of CFCs and generated lower NO_x compared to the process for gas motor. This difference in process emissions does not necessarily discredit gas utilization, but signals the importance of choosing the right technology, which would ensure emission reduction across the board.

Fig. 1-24 – Normalized results in mili Person Equivalents (mPE) for Category 1 systems for: Climate Change (GWP), Ozone Depletion (ODP), Human Toxicity, Cancer Effects (HT, CE), Human Toxicity, non Cancer Effects (HT, non CE), Particulate Matter (PT), Photochemical Ozone Formation (POF), Terrestrial Acidification (TAD), Eutrophication Terrestrial (EPT), Eutrophication Freshwater (EPF), Eutrophication Marine (EPM), Ecotoxicity Freshwater (ECF) and Depletion of Abiotic resources, Mineral fossil and Renewable (DAMR).

Scenario 1.e, with the combustion WtE plant, performed best in several categories. However, for categories POF, TAD, and EPT it also presented the highest impacts. These high impacts once more came mainly from NO_x emissions. Nevertheless, energy recovery and substitution of marginal electricity scenario 1.e contributed significant savings in GWP, ODP, HT (CE), PT, EPF, ECF and DAMR (due to steel recycling). The results of this scenario are similar to those of Reichert and Mendes (2014) and confirm that strategies based on energy recovery are not significantly better than sanitary landfilling, even if they displace natural gas based electricity.

3.2.2 Systems based on source separation into wet and dry streams (category 2)

Fig. 1-25 captures the breakdown of normalized results for the second category systems, which are based on source separation of dry-wet streams in a ratio of 20:80. The first two systems variants, 2.a and 2.b, combine dry stream sorting and subsequent materials recycling with simple disposal of the wet stream by sanitary landfilling. Variants from 2.c to 2.e include wet stream pre-treatment and composting (2.c) or anaerobic digestion (2.d and 2.e).

Fig. 1-25- Normalized results in mili Person Equivalents (mPE) for Category 2 systems for Climate Change (GWP), Ozone Depletion (ODP), Human Toxicity, Cancer Effects (HT, CE), Human Toxicity, non Cancer Effects (HT, non CE), Particulate Matter (PT), Photochemical Ozone Formation (POF), Terrestrial Acidification (TAD), Eutrophication Terrestrial (EPT), Eutrophication Freshwater (EPF), Eutrophication Marine (EPM), Ecotoxicity Freshwater (ECF) and Depletion of Abiotic resources, Mineral fossil and Renewable (DAMR).

In systems 2.a and 2.b, around 11% and 12% per FU, of waste materials are directed to recycling after sorting of the dry stream. It can be noticed that emissions from landfiling in scenarios 2.a and 2.b in general overcame potential savings from materials recycling, for GWP, ODP, HT (non CE), EPM and ECF. Nevertheless, dry stream recycling contributed savings in almost all impact categories. For example, GWP was halved compared to complete mixed waste sanitary landfiling in 1.c. Operation of the MRFs had an insignificant impact.

Further on, the addition of wet stream treatment resulted in interesting observations. At first glance results suggested system 2.c(e), which is based on wet stream enclosed composting, as having the least impact in most categories. Open air windrow composting (2.c(w)) was

affected by larger emissions to air than enclosed composting and further, as the process was also modelled for digestate stabilization, it negatively affected all scenario systems based on wet stream digestion. In scenarios with digestion, although methane is largely removed (aside from fugitive emissions), N-based emissions remain largely unchanged. The potential impacts are connected to input and process specific emissions of methane, N_2O , NH_3 and NMVOCs. The system choice for digestate stabilization was thus indicated as a hot spot and tested in a specific sensitivity analysis, which changed substantially the initial picture.

Compost and stabilized digestate application on (agricultural) soil also displayed relatively extreme results, either savings in HT, CE and EPF or high burdens in HT, non CE, EPM and ECF. The process displayed in Fig. 1-25, named “avoided fertilizer”, accounts the net effect of application to soil and avoided mineral fertilizers. The savings were tracked to heavy metals, specifically chromium that is avoided from the use of the mineral fertilizers. The burdens were similarly traced to heavy metals (chromium, nickel, lead and mercury) present in the compost after the treatment of the wet fraction. More precisely, the heavy metals came from the fraction “other non-combustibles” part of waste matrix. The systems with wet digestion, which included a secondary pre-treatment, namely pulping, had a smaller impact in HT, non CE and ECF, due to the better overall removal of this fraction from the input to the digestion process.

Lastly, both systems with dry and wet digestions produced similar amounts of biogas, with the slightly higher wet digestion efficiency being compensated by additional loss of organics in the pulping process. Utilization of the biogas directly for electricity production resulted in small savings in several categories, while biogas upgrading and utilization as vehicle fuel showed significantly higher benefits (scenarios 2.d(u) and 2.e(u)).

3.2.3 Systems based on mechanical-biological treatment (category 3)

The results for category three systems are illustrated in Fig. 1-26. System variants here achieved net savings in all but a few impact categories, the results being relatively similar, but favouring to some extent the two variants based on mixed waste treatment in biological drying MBTs. The operation of the MBTs, just like MRFs in category two systems, did not incur any significant impacts. RDF production and utilization in cement manufacturing contributed large savings connected to avoided petroleum coke production and combustion. Direct emissions from RDF combustion resulted in a bigger impact, compared to savings by avoided coke, in only one impact category, namely HT, non CE. The contribution to this impact was due to release to air of volatile heavy metals (specifically Hg and Pb). Considering that no specific and

intensive mechanical treatment of the RDF was included to upgrade this treatment output, the results are positive towards demonstrating the big potential for the application of RDF in the cement industry in Brazil.

Around 14% of the input waste was further recovered in outputs destined for recycling (i.e. metals, plastics, paper and cardboard) in system variants 3.b and 3.d, which intended to represent versions of facilities where material recovery would take place besides treatment of the organics and RDF production. In these variants recycling contributed significant savings to different impact categories.

“Land reclamation”, which is a low-grade utilization of the compost-like output or stabilized digestate from aerobic or aerobic-anaerobic MBTs respectively, resulted in impacts for HT, CE and ECF due to heavy metals (zinc, copper and chromium mainly). This was not unexpected, as these systems have input mixed waste and the stabilized outputs would typically not achieve the requirements to be used as fertilizer, without substantial pre- or post-processing.

Fig. 1-26- Normalized results in mili Person Equivalents (mPE) for Category 3 systems for Climate Change (GWP), Ozone Depletion (ODP), Human Toxicity, Cancer Effects (HT, CE), Human Toxicity, non Cancer Effects (HT, non CE), Particulate Matter (PT), Photochemical Ozone Formation (POF), Terrestrial Acidification (TAD), Eutrophication Terrestrial (EPT), Eutrophication Freshwater (EPF), Eutrophication Marine (EPM), Ecotoxicity Freshwater (ECF) and Depletion of Abiotic resources, Mineral fossil and Renewable (DAMR).

3.3 Sensitivity results

All the parameters that were tested for the sensitivity showed the new results that are presented in Table 1-22. 1.c(s) and 1.d(s) refer to the carbon storage sensitivity; e – refers to the electricity sensitivity for scenarios 1.d, 1.e, 2.d and 2.e; PC – refers to the post composting sensitivity and it was tested for scenarios 2.d, 2.d(u), 2.e and 2.e(u); and AC – refers to the avoided coked ratio modified in scenarios 3.

Table 1-22 - Characterized sensitivity results for all parameters modified.

Category	Scenario	Baseline	Sensitivity	Category	Scenario	Baseline	Sensitivity
GWP (100)	1.c(s)	255.9857	464.7001		e – 2.d	0.000486	0.000481
	1.d(s)	207.3519	416.0663		e – 2.e	0.000217	0.000215
	e – 1.d	207.3519	235.3512		PC – 2.d	0.000486	0.000486
	e – 1.e	213.8571	378.4676		PC – 2.d(u)	0.000483	0.000483
	e – 2.d	35.57285	60.4606		PC – 2.e	0.000217	0.000219
	e – 2.e	33.87917	61.33431		PC – 2.e(u)	0.000214	0.000216
	PC – 2.d	35.57285	-130.129	PT	e – 1.d	0.01165	0.000348
	PC – 2.d(u)	-11.1386	-176.841		e – 1.e	-0.00853	-0.07293
	PC – 2.e	33.87917	-113.775		e – 2.d	0.113019	0.103173
	PC – 2.e(u)	-15.2017	-158.667		e – 2.e	0.103006	0.094025
	AC – 3.a	-794.15	-714.735		PC – 2.d	0.113019	-0.05499
	AC – 3.b	-384.05	-345.648		PC – 2.d(u)	0.065318	-0.10269
	AC – 3.b(u)	-384.05	-345.648		PC – 2.e	0.103006	-0.05293
	AC – 3.c	-937.44	-843.7		PC – 2.e(u)	0.052377	-0.10358
	AC – 3.d	-537.70	-483.927	POF	e – 1.d	0.677174	0.637669
ODP	e – 1.d	0.000388	0.00039		e – 1.e	0.672033	0.441834
	e – 1.e	-1.8E-05	-5.9E-06		e – 2.d	0.717218	0.682327
	e – 2.d	2.31E-05	2.5E-05		e – 2.e	0.228377	0.250867
	e – 2.e	-3.3E-05	3.55E-05		PC – 2.d	0.717218	-0.18266
	PC – 2.d	2.31E-05	2.34E-05		PC – 2.d(u)	-0.0084	-0.90828
	PC – 2.d(u)	9.79E-06	1.01E-05		PC – 2.e	0.228377	-0.19194
	PC – 2.e	-3.3E-05	3.37E-05		PC – 2.e(u)	-0.54096	-0.96245
	PC – 2.e(u)	-4.7E-05	1.82E-05	TAD	e – 1.d	0.350681	0.29119
HT, CE	e – 1.d	2.3E-07	1.57E-07		e – 1.e	0.540146	0.23461
	e – 1.e	-5.7E-07	-1E-06		e – 2.d	7.487289	7.438703
	e – 2.d	-5.2E-06	-5.2E-06		e – 2.e	6.989685	6.933457
	e – 2.e	-6.1E-06	-6.1E-06		PC – 2.d	7.487289	-0.12643
	PC – 2.d	-5.2E-06	-5.2E-06		PC – 2.d(u)	7.092786	-0.52094
	PC – 2.d(u)	-5.3E-06	-5.3E-06		PC – 2.e	6.989685	-0.09607
	PC – 2.e	-6.1E-06	-6E-06		PC – 2.e(u)	6.571426	-0.5148
	PC – 2.e(u)	-6.3E-06	-6.2E-06	EPT	e – 1.d	1.948205	1.796602
HT, non CE	e – 1.d	7.78E-06	1.41E-06		e – 1.e	3.434363	2.53959
	e – 1.e	8.18E-06	-2.9E-05		e – 2.d	34.84774	34.7127

Category	Scenario	Baseline	Sensitivity
	e – 2.e	32.44534	32.39153
	PC – 2.d	34.84774	0.874125
	PC – 2.d(u)	33.51333	-0.46028
	PC – 2.e	32.44534	0.814577
	PC – 2.e(u)	31.03166	-0.60068
EPF	e – 1.d	0.00135	0.000721
	e – 1.e	-0.00069	-0.00442
	e – 2.d	-0.01911	-0.01967
	e – 2.e	-0.0187	-0.01873
	PC – 2.d	-0.01911	-0.0191
	PC – 2.d(u)	-0.02135	-0.02134
	PC – 2.e	-0.0187	-0.01828
	PC – 2.e(u)	-0.02107	-0.02067
EPM	e – 1.d	0.210887	0.194816
	e – 1.e	0.315705	0.220864
	e – 2.d	0.493921	0.479606
	e – 2.e	0.452343	0.455332
	PC – 2.d	0.493921	0.258964
	PC – 2.d(u)	0.369312	0.134356
	PC – 2.e	0.452343	0.249177
	PC – 2.e(u)	0.320326	0.116731
ECF	e – 1.d	69.6223	72.64014
	e – 1.e	-82.5009	-68.6515
	e – 2.d	90.86629	93.17272
	e – 2.e	-0.07117	29.31415
	PC – 2.d	90.86629	92.52545
	PC – 2.d(u)	96.38805	98.04721
	PC – 2.e	-0.07117	25.39713
	PC – 2.e(u)	5.809048	30.54207
DAMR	e – 1.d	-1.4E-06	-0.00018
	e – 1.e	-0.00037	-0.00142
	e – 2.d	-0.00194	-0.0021
	e – 2.e	-0.00194	-0.00207
	PC – 2.d	-0.00194	-0.00194
	PC – 2.d(u)	-0.00217	-0.00217
	PC – 2.e	-0.00194	-0.00194
	PC – 2.e(u)	-0.00218	-0.00218

The results for climate change can be observed in Fig. 1-27 where they are compared with the baseline net results. Setting carbon storage in sanitary landfills to 0% after 100 years, resulted in almost doubling of the GWP impact (81% increase for 1.c and 100% for 1.d). This change would favour combustion WtE as the better alternative to direct disposal of mixed waste. The change in this parameter does not affect other impact categories. The change of digestate post-treatment technology from open windrows composting to enclosed composting for system scenarios 2.d, 2.d(u), 2.e and 2.e(u), resulted, as expected, in a substantial performance improvement in all the categories previously dominated by air emissions from open composting (i.e. GWP, PT, POF, TAD, EPT and EPM).

Replacing marginal electricity (i.e. based on combined cycle natural gas) with the Brazilian average production mix in the scenarios with avoided electricity, i.e. 1.d, 1.e, 2.d and 2.e., resulted in an increase of GWP. However, only 1.e (combustion WtE) was severely affected, with almost doubling the GWP impact. Impact in other categories did not increase, but on the contrary, HT, non CE and TAD decreased for all the scenarios. This was tracked to avoided emissions of zinc and arsenic from ethanol production, which is part of the Brazilian electricity mix.

Lastly, a decrease in coke substitution ratio in category three systems, from 1:1 to 1:0.9, resulted in proportional effects in relevant savings. The 10% change in the substitution ratio, affected especially systems in 3.a and 3.c, determining a decrease in GWP savings by 22%-25% (from -318 to -238), while systems 3.b and 3.d displayed a decrease of only 11%-13%.

Fig. 1-27- Sensitivity results in kg CO₂ eq. for Climate Change (GWP).

4 Discussion

The system scenarios evaluated in this work were intended to be technology-centric, and thus as potential management scenarios for Brazil they are not at all exhaustive, especially if

one is to consider the variety of technology combinations possible. This work thus mainly clarifies the potential environmental burdens and benefits of the techniques compared, which should then be used in the planning of integrated management systems that consider particularities of specific catchment areas (e.g. population density, socio-economic conditions). The impacts of current management of collected MSW in Brazil can be very roughly estimated by aggregating systems 1.a, 1.b and 1.c analysed here. The normalized results for this exercise are illustrated in Fig. 1-28. For GWP, as example, they suggest a potential impact of 626 kg CO₂ eq. t⁻¹, which extrapolated to national level would account for around 48 million t of CO₂ eq. related to the disposal of MSW collected in one year.

Fig. 1-28- Impact for the average management of MSW collected in Brazil in 2016, considering the ratios given in the introduction (17% semi-controlled dumps, 25% controlled dumps and respectively 54% sanitary landfills with gas flaring).

Separate collection programmes are slowly expanding in Brazil, but not uniformly, as they are typically implemented in limited (typically affluent) areas. Where dry recyclables collection has been implemented, even after many years, diversion rates only reach around 10% (Ibáñez-Forés et al., 2017). Separate collection based on a three-stream system (dry recycling, biowaste and residual waste) is theoretically possible, but realistically unlikely to have significant coverage in short-to-medium term. Nevertheless, in this work, we observed that simple dry-wet collection could pose problems with regard to the possible quality of compost outputs, as the wet stream is still contaminated even with comprehensive pre- and post-treatment. Separate collection of only biowaste is of course not a guarantee that the stream will be substantially cleaner, but it should be especially prioritized in cases where large homogeneous quantities are generated, such as retail, service industry and food production.

From scenarios 2.a, 2.b, 3.a and 3.b it was possible to calculate theoretical recycling rates for the scenarios (on dry recyclables). The highest recycling rate was achieved in scenario

3.b and 3.d, with a 14.5% recovery rate. The presence of MRFs and MBTs with expanded sorting to recover various materials for recycling is fully established in places such as North America and Europe. In Europe, materials recovery from residual waste is increasingly seen as a solution to areas with inherently low citizen participation in separate collection, such as urban areas with high population densities and regions where cultural and socio-economic barriers persist (Trulli et al., 2018). The efficiency of such recovery systems has been confirmed, even when compared to or supplementing well running separate collection systems (Brouwer et al., 2018; Dahlbo, Poliakova, Mylläri, Sahimaa, & Anderson, 2018; Feil, Pretz, Jansen, & Thoden Van Velzen, 2017). The present work also confirms their environmental feasibility in a Brazilian context. Further, MBT systems can be modular, with various degrees of automation and corresponding manual labor requirements, and connected infrastructure costs, fitting various local situations.

In Brazil, there is considerable urgency for both comprehensive, science informed, long-term strategy planning and immediate action to mitigate the impact of current improper practices. Progress on the ground is slowed by considerable economic, social and local political challenges (Campos, 2014). As put by Rodić and Wilson (2017), “no technology could on its own solve the problems related to economic and social sustainability of waste management activities”, pointing further out that necessary action in developing countries has to be focused on governance issues. Comprehensive analyses of MSW management in Brazil are further hindered by several aspects. Brazil does not have standards for waste gravimetric analysis, such as for which fractions to consider and how to deliver the results. Therefore, the data found regarding waste compositions has uncertainties that are difficult to estimate. Furthermore, physico-chemical properties used in most studies to date, including the present work, are not based on analyses of Brazilian waste. Variations in composition and physico-chemical properties can alter, sometimes significantly, LCA results (Bisinella et al., 2017). Another aspect that limits precision, is the always present intervention by the informal sector, which plays an important role in the waste management system in Brazil. The efficiency and scale of their interception is difficult to measure and thus typically ignored. Most municipal analyses do not even mention these workers, which limits the possibility to include environmental, economic and social contributions of the informal sector to the whole system.

5 Conclusions

This comparison between three different sets (categories) of systems provides an overview of the current and alternative technology-centric waste management alternatives for

Brazil. The first category of systems assessed options for direct disposal of MSW, including still prominent improper waste disposal systems in Brazil, namely dumps, alongside sanitary landfills and combustion WtE. The results confirmed the high environmental cost of improper disposal (still 41.6% of the current disposal in Brazil) and provided evidence that combustion WtE does not offer significant benefits over sanitary landfilling, due to limitations in energy utilization and the low-carbon background electricity system. Category two of systems, based on source separation into wet and dry streams, showed a better environmental performance. Recycling contributed significant savings, however particular attention needs to be focused on treatment of biodegradable waste. The use of technologies including treatment of air emissions from degradation processes were shown essential, even after prior anaerobic digestion processes. Biogas upgrading and use as vehicle fuel resulted in bigger savings compared to electricity production. The use of compost outputs was indicated as potentially detrimental due to contamination levels (heavy metals) in the wet stream. As for category three systems, mechanical-biological systems had environmental benefits in most impact categories. The major contributor was RDF production and utilization in cement production, substituting petroleum coke. MSW-derived RDF utilization needs further investigation in a Brazilian context, to test technical and economic feasibility and validate environmental feasibility. Lastly, MBT systems that include extended capabilities to recover recyclable materials, could also make significant contributions to recycling in Brazil.

References

“All references are presented in the end of this document.”

CHAPTER 3 - LIFE CYCLE ASSESSMENT OF PROSPECTIVE MSW MANAGEMENT BASED ON INTEGRATED MANAGEMENT PLANNING IN CAMPO GRANDE, BRAZIL

Adapted from: **Lima, P.D.M.**, Olivo, F., Paulo, P.L., Schalch, V., Cimpan, C. (2019) Life Cycle Assessment of Prospective MSW Management based on Integrated Management Planning in Campo Grande, Brazil. *Waste Management* 90:59-71. doi: 10.1016/j.wasman.2019.04.035.

Graphical Abstract

Abstract

A crucial first step in transforming problematic waste management into sustainable integrated systems is comprehensive planning and analysis of environmental and socio-economic effects. The work presented here is a Life Cycle Assessment (LCA) that addressed the environmental performance of prospective development pathways for the municipal solid waste (MSW) management system in a large urban area, i.e. Campo Grande, Brazil. The research built on data and expanded the main development pathway proposed in the municipalities integrated waste management plan, which covers a period of 20 years (2017 to 2037). The system progression was assessed for milestone years (5-year intervals) considering projections of future population and waste generation growth, as well as addressing the development of surrounding systems, such as energy production. Results reveal that the rather conservative planned development pathway, which is largely based on gradual increase in selective collection, could successfully counter negative environmental externalities that would otherwise materialize due to increasing waste generation. A second, more ambitious, pathway with additionally scheduled actions to treat mixed MSW and upgrade certain treatment technologies (e.g. from composting to anaerobic digestion of collected organics), was used to illustrate a potential range for

significantly higher impact reduction and even positive externalities, given a zero burden approach before waste generation.

Keywords: Municipal Solid Waste (MSW), Life Cycle Assessment (LCA), prospective scenarios, cooperatives, recycling, mechanical-biological treatment.

1 Introduction

Brazil is the world's fifth most populated and fifth largest country by land area. As a country still in the course of joining advanced industrialized economies, Brazil faces substantial challenges with regard to current and future solid waste management (Alfaia et al., 2017). In 2016, Brazil generated 78.3 million tonnes of municipal solid waste (MSW) (ABRELPE, 2017). Collection coverage still hovers around 90%, while 40% of collected MSW is disposed of in unsanitary conditions (ABRELPE, 2017). Recycling and biological treatment make up together less than 5% of MSW management. These national figures indicate environmental, social and economic missed opportunities and come into contrast with the fact that Brazil has both a comprehensive national solid waste management policy and a national climate policy.

The National Solid Waste Policy (PNRS – Federal law nº 12,305) adopted in 2010, established general principles and objectives for Brazil, such as elimination of open dumps, the increase of selective collection and reverse logistics coverage and the inclusion of waste pickers in strategic planning (with incentives to formalize the activity through cooperatives) (Brasil, 2010). Although ambitious, the PNRS lacks comprehensive quantitative goals (targets) and transfers the responsibility for achieving objectives to municipal authorities. This aspect combined with a general difficulty in Brazil to integrate politically and administratively the different levels of government, especially the national and local level, was identified by some authors as a main reason for the failure of the PNRS implementation to date (Maiello et al., 2018a). One of the main requirements of the PNRS is the elaboration, by all municipalities, of integrated Municipal Solid Waste (MSW) management plans that include system planning, future management actions and targets for reduction, reuse and recycling of waste. Brazil has also a National Policy on Climate Change (PNMC) and is part of the Paris agreement, with a pledge to reduce Greenhouse Gas (GHG) emissions by 37% compared to 2005 levels (Brasil, 2008; Lin, 2017). Waste is estimated responsible for 4% of the total GHG emissions accounted in the national inventory (Observatório do Clima, 2018). However, recent development in GHG emissions shows that the country is moving further away from the targets (Climate Analytics et al., 2018; Observatório do Clima, 2018).

Campo Grande, the state capital of Mato Grosso do Sul, located in west central Brazil, first adopted an integrated waste management plan in 2008, which was updated with a comprehensive implementation plan published in 2017 (PMCG and DMTR, 2017). Campo Grande is an urban centre with a total population of 874,000 inhabitants and an average waste generation of about 270,000 t.year⁻¹ (IBGE, 2017). MSW management here has been undergoing significant changes in the last few years. In 2012, both a new sanitary landfill was opened and the city formally implemented selective collection of dry recyclable materials. Informal waste pickers have self-organized in seven cooperatives, four of which operate a sorting unit for the selective collection since 2015. By formal agreement with the municipal authorities, they are responsible for sorting, selling and packing all the recyclables received at the sorting unit.

The work presented herein reports an environmental assessment of the current and prospective development pathways for MSW management in Campo Grande. The research expanded the main development pathway presented in the municipalities' updated waste plan, which covers a period of 20 years, between 2017 and 2037. Comprehensive environmental assessment studies addressing complete waste management systems in Brazil are still few, although increasing in number following the adoption of the PNRS. Data availability remains a barrier to Life Cycle Assessment (LCA) studies, e.g. lack of access to or missing data on waste management, as well as a lack of geographically-relevant Life Cycle Inventories (LCI) in mainstream (LCA) databases and assessment tools (Ibáñez-Forés et al., 2017).

Previous LCAs have addressed different treatment possibilities for specific MSW streams, such as mixed waste (Leme et al., 2014; Lima et al., 2018; Mendes et al., 2004; Soares, 2017), as well as biodegradable and recyclable streams (e.g. Bernstad Saraiva et al., 2017; Lima et al., 2018a). These studies show that the prevalent current practice of landfilling of mixed waste has high environmental impact compared to waste incineration and Mechanical Biological Treatment (MBT). However, waste incineration with recovery of electricity does not perform much better than sanitary landfilling with gas valorization, due to the low impact of avoided electricity production, which in the case of Brazil is largely from renewable sources. A growing number of studies address partial (e.g. Liikanen et al., 2018) or full management systems that compare largely theoretical system scenarios (Goulart Coelho and Lange, 2018; Mersoni and Reichert, 2017; Reichert and Mendes, 2014) to the current management in different municipalities. Many of these case studies refer geographically to the populous southeast Brazil (e.g. São Paulo). Most studies agree, finding that selective collection, recycling and biological treatment of organic waste should be prioritized, while MBT with production of

refuse-derived fuel (RDF) is indicated as advantageous for the treatment of remaining mixed waste. The recent publication by Ibáñez-Forés et al. (2018), is distinct because it presented the evolution of a MSW system (in João Pessoa, Brazil) and its environmental performance, retrospectively between 2005 and 2015.

The objective of the present study was to evaluate the environmental performance of planned development in the municipality, and also to explore more broadly potential effects of additional ambitious actions towards sustainable waste management. The assessment work is unique for Brazil because: (1) it builds on extensive primary data and analyses undertaken for elaboration of the integrated management plan in Campo Grande, and (2) it assesses prospective system development in a large urban area, including both projections of future population and waste generation growth, as well as addressing the development of surrounding systems, such as energy production.

2 Materials and methods

2.1 Study area and reference data

In 2017 the municipal authorities of Campo Grande published the Plan of Selective Collection (PCS – Plano de Coleta Seletiva in portuguese), a detailed implementation plan for the integrated waste management plan adopted several years previous. The PCS was prepared over a period of two years and addressed all major waste streams generated in the municipality: MSW (household and similar commercial/institutional), construction and demolition waste, bulky waste and waste with mandatory reverse logistics (i.e. electronics, tires, batteries, lighting equipment and chemicals). The PCS consists of four comprehensive reports (volumes 1-4) containing (PMCG and DMTR, 2017): (1) a background analysis of the current waste management situation and relevant socioeconomic and environmental aspects; (2) projections for population and waste generation, and scenarios regarding separate collection; (3) detailed goals, projects and actions for the next 20 years; and (4) operationalization of the new systems, including detailed planning of infrastructure and costs of implementation. The PCS was additionally supported by a comprehensive physical characterization study for the MSW streams.

The present environmental assessment was elaborated based on data produced for the PCS. However, the study focused solely on the MSW streams, mainly due to the large level of detail in the PCS and the availability of physical characterization data. Nevertheless, a number of updates were made to the original PCS projections, as well as a further specification of

2.1.1 Gravimetric compositions and waste generation rates

In Campo Grande, MSW is collected in three ways: (1) mixed waste collection covering the entire municipality (termed regular collection), (2) door-to-door selective collection for mixed recyclables, and (3) a number of voluntary drop-off points (termed ecopoints, "LEVs" in portuguese). The physical characterization study performed by DMTR, covered all three schemes. In the APPENDIX B the description of the methodology can be found as the sector-wise gravimetric compositions (Table B-1 and Table B-).

Table 2-1 – Summary of gravimetric compositions for the waste streams included in this work; given in percentage wet weight.

Waste category	Regular mixed waste [wt %]	Door-to- door selective [wt %]	Ecopoints [wt %]	Biowaste [wt %]	Street [wt %]	Markets [wt %]	Parks [wt %]
Paper	2.44	9.78	7.91	0.71	2.23	-	-
Multilayer packaging	0.99	3.72	1.84	3.51	0.30	-	-
Cardboard	9.21	18.75	41.33	2.05	6.77	-	-
Metals	0.92	4.44	2.12	0.64	0.60	-	-
Glass	2.61	16.10	21.05	0.32	1.24	-	-
Plastics	20.80	23.71	17.10	7.98	9.69	15.80	-
Organic	46.63	0.81	-	65.02	19.26	84.20	99.60
Other combustibles	11.45	1.35	-	2.55	1.50	-	-
Other non-combustibles	4.89	21.34	8.65	17.21	58.41	-	0.40
Hazardous	0.06	-	-	-	-	-	-
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00	100.00

However, the waste characterization study performed by DMTR did not cover some of the waste streams that were included in the present environmental assessment. . We further distinguished several MSW streams in the municipality based on the quantity (per year) estimates provided by DMTR and SOLURB, namely waste from street cleaning, parks and markets. These streams are currently collected with other regular mixed MSW and landfilled. The possible composition for biowaste, a stream that is not separately collected today, was adapted from Naroznova et al. (2016) considering a much higher rate of miss-sorting by households (i.e. 35% unwanted materials in biowaste). For waste from street cleaning, parks and markets, the gravimetric compositions were compiled, considering local conditions, from Boldrin & Christensen (2010), Das Neves & Tucci (2011), de Oliveira (2012) and Vaz et al.

(2003), due to the lack of onsite data. Table 2-2 presents the detailed waste fractions employed in the modelling and Table 2-8 shows the summary of the waste stream compositions used in this work.

Table 2-2 – Gravimetric composition of each stream considered for the modelling.

Waste fraction	Regular mixed waste [wt %]	Door- to-door selective [wt %]	Ecopoints [wt %]	Biowaste [wt %]	Street [wt %]	Markets [wt %]	Parks [wt %]
Paper	2.44%	9.78%	7.91%	0.71%	2.23%	0.00%	0.00%
Office Paper	1.54%	3.27%	2.19%	0.71%	-	-	-
Other Clean Paper	0.90%	6.51%	5.72%	-	2.23%	-	-
Multilayer Packaging (Juice cartons)	0.99%	3.72%	1.84%	3.51%	0.30%	0.00%	0.00%
Other Clean Cardboard	9.21%	18.75%	41.33%	2.05%	6.77%	0.00%	0.00%
Metals	0.92%	4.44%	2.12%	0.64%	0.60%	0.00%	0.00%
Food cans	0.57%	2.70%	1.11%	0.64%	0.39%	-	-
Beverage cans	0.32%	1.73%	1.01%	-	0.21%	-	-
Glass	2.61%	16.10%	21.05%	0.32%	1.24%	0.00%	0.00%
Clear Glass	0.57%	2.42%	4.41%	-	0.27%	-	-
Brown Glass	2.04%	13.68%	16.64%	0.32%	0.97%	-	-
Plastics	20.80%	23.71%	17.10%	7.98%	9.69%	15.8%	0.00%
Hard Plastic	1.67%	6.64%	4.09%	-	2.07%	-	-
Plastic Bottles	1.23%	5.70%	2.36%	-	0.76%	-	-
Plastic Products	0.92%	3.63%	3.68%	3.51%	-	-	-
Non-Recyclable Plastic	0.42%	0.50%	0.21%	-	0.48%	7.6%	-
Soft Plastic	16.56%	7.25%	6.76%	4.47%	6.38%	8.2%	-
Organic	46.63%	0.81%	0.00%	65.02%	19.26%	84.2%	99.6%
Vegetable Food Waste	41.03%	0.71%	0.00%	52.53%	6.22%	74.1%	-
Animal Food Waste	5.60%	0.10%	0.00%	12.49%	-	10.1%	-
Small Stuff	-	-	-	-	12.44%	-	75.6%
Branches	-	-	-	-	0.60%	-	19.5%
Wood	-	-	-	-	-	-	4.5%
Other combustibles	11.45%	1.35%	0.00%	2.55%	1.50%	0.00%	0.00%
Diapers, sanitary towels, tampons	11.45%	1.35%	0.00%	2.55%	-	-	-
Textiles	-	-	-	-	1.50%	-	-
Other (non-combustibles)	4.89%	21.34%	8.67%	17.21%	58.41%	0.00%	0.40%
Stones	-	-	-	-	14.20%	-	0.20%
Other Non-combustibles	4.89%	21.34%	8.67%	17.21%	44.21%	-	0.20%
Hazardous (Batteries)	0.06%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
TOTAL	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Source: (Boldrin & Christensen, 2010; Das Neves & Tucci, 2011; de Oliveira, 2012; Naroznova, Møller, & Scheutz, 2016; PMCG & DMTR, 2017a; Vaz, Costa, Gusmão, & Azevedo, 2003)

Per capita household MSW generation rates in the four socio-economic sectors were elaborated for the PCS by Manzi (2017), who considered the concurrent evolution of collected waste amounts and population in representative areas in the four socio-economic sectors over a number of previous years (Manzi, 2017). Fig. 2-2 shows the per capita generation in each one of the sectors obtained by Manzi (2017).

Fig. 2-2 –Waste generation per capita for the different sectors in Campo Grande. Source: Adapted from Manzi (2017).

2.1.2 Projections of future population, waste generation and separate collection

The PCS was framed by potential growth in waste generation in the 20 years period covered, as a result of both population and economic growth. Population increase was projected in the planning phase based on simple linear regression, using census data between 2000 and 2010, resulting in a 30% increase over the whole period (PMCG and DMTR, 2017). Table 2-3 shows the calculated population per sector, provided by DMTR.

Table 2-3 – Total urban population and per sector in the municipality projected until 2037.

Year	Urban population	"until 2.5"	"from 2.51 to 5.00"	"from 5.01 to 7.50"	"from 7.51 to 10.00"
2017	857,808	97,267	487,887	215,764	56,890
2018	870,650	98,723	495,191	218,995	57,741
2019	883,490	100,179	502,494	222,224	58,593
2020	896,330	101,635	509,797	225,454	59,445
2021	909,172	103,091	517,101	228,684	60,296
2022	922,011	104,547	524,403	231,913	61,148
2023	934,854	106,003	531,707	235,144	61,999
2024	947,694	107,459	539,010	238,373	62,851
2025	960,535	108,915	546,314	241,603	63,703
2026	973,375	110,371	553,617	244,833	64,554
2027	986,216	111,827	560,920	248,063	65,406
2028	999,057	113,283	568,223	251,293	66,257
2029	1,011,897	114,739	575,526	254,522	67,109
2030	1,024,739	116,195	582,830	257,753	67,961
2031	1,037,581	117,652	590,134	260,983	68,812
2032	1,050,420	119,107	597,437	264,212	69,664
2033	1,063,261	120,563	604,740	267,442	70,515

Year	Urban population	"until 2.5"	"from 2.51 to 5.00"	"from 5.01 to 7.50"	"from 7.51 to 10.00"
2034	1,076,101	122,019	612,043	270,672	71,367
2035	1,088,944	123,476	619,348	273,902	72,219
2036	1,101,784	124,932	626,650	277,132	73,070
2037	1,114,625	126,388	633,954	280,362	73,922

Source: (PMCG & DMTR, 2017c)

Projection for all MSW streams were made by applying a consistent growth rate of 0.5% per year to the per capita generation rates and combining that with the population projection over the period, which led to a 44% increase in total waste production over the period. In terms of waste compositions, it was assumed that the overall composition of the waste would not change significantly over the period.

In the present study, we maintained the underlying projections in the PCS, however, we corrected the starting point with newly available data, i.e. the total MSW generated in 2017 (271,267 t). Furthermore, the baseline (or starting quantity of) MSW streams in 2017 were elaborated with the following approach. First, the mixed waste (regular collection) from households was calculated using the generation rates per capita in the four sectors and their respective population, resulting in a total of 222,671 t. Next, total MSW originating at the households was determined by adding any selective collection streams to the previous amount, resulting in 229,923 t. The remaining difference to the total MSW generated in 2017, was then assumed to account for other MSW streams. Street cleaning, parks and markets totalled 13,379 t in 2017. The remaining difference, 27,966 t, was then assigned as MSW generated by services, commerce and institutions in the municipality. Once the 2017 baseline was established, the projection of future waste generation was performed as described above, i.e. with a consistent growth rate for all streams. The total household waste generated is presented in Table 2-4. The baseline amounts are presented in the 2017 column of Table 2-5.

Table 2-4 – Household waste amounts per sector for 2017.

Sector	Quantity (tonnes/year)	Per capita (kg/inhab/day)
"until 2.5"	20,591.4	0.58
"from 2.51 to 5.00"	124,655.1	0.70
"from 5.01 to 7.50"	57,490.3	0.73
"from 7.51 to 10.00"	19,934.3	0.96
TOTAL	222,671.1	0.711

Source: (Manzi, 2017)

Table 2-5– Summary waste generation in tonnes per year for the milestone years, and related urban population.

Population (urban)	2017	2022	2027	2032	2037
	857,808	922,011	986,216	1,050,420	1,114,625
MSW Waste streams					
Household waste (HHW)	229,922.6	253,371.6	277,858.8	303,420.9	330,097.0
<i>Regular collection (mixed waste)</i>	<i>222,671.1</i>	<i>233,220.4</i>	<i>247,918.6</i>	<i>232,208.9</i>	<i>234,728.6</i>
<i>Door to door selective</i>	<i>6,692.9</i>	<i>18,417.8</i>	<i>27,445.2</i>	<i>35,289.5</i>	<i>41,073.8</i>
<i>Ecopoints selective</i>	<i>558.5</i>	<i>1,733.4</i>	<i>2,495.0</i>	<i>3,113.8</i>	<i>3,952.12</i>
<i>Biowaste selective</i>	-	-	-	<i>32,808.7</i>	<i>50,342.4</i>
Commercial and institutional	27,965.9	30,818.0	33,796.5	36,905.6	40,150.3
Street cleaning	5028.7	5,541.5	6,077.1	6,636.2	7,219.6
Parks	7754.4	8,545.2	9,371.1	10,233.2	11,132.9
Markets	595.6	656.3	719.7	785.9	855.0
TOTAL MSW	271,267.1	298,932.6	327,823.2	357,981.8	389,454.8

Source: adapted from PMCG and DMTR (2017c).

Regarding the future development of waste management in Campo Grande, the PCS constructed a comprehensive scenario revolving around the gradual expansion (in coverage and public participation) of separate collection. More specifically, this addressed collection of mixed recyclable materials in the door-to-door selective scheme, expansion of the drop-off collection points (ecopoints) and a new scheme called “spiral collection” which will cover the less developed urban areas. The latter will be operated as a door-to-door scheme directly by the remaining three cooperatives of waste pickers (COOPERNOVA, COOPERSOL and COOPERVIDA). Lastly, a separate biowaste (food waste) stream was planned from 2028 onwards, which would be destined for a composting plant. The amounts projected for these separate streams were calculated by maintaining the PCS goals and are summarized in Table 2-5 for the milestone years and detailed in Table 2-6 and Table 2-7 below. Essentially, these projections account for the gradual increase of the separated streams of recyclables from 7.5% of the total potential (generated recyclable fractions in MSW) in 2017 to 32% in 2037. For biowaste, it was assumed that the separate stream would grow linearly from 1% of the potential organic fraction in MSW in 2028 up to 30% in 2037 (parks and markets not included).

Table 2-6 – Potential for dry recyclables of HHW and CMW, targets for each selective collection and its respective masses.

Year	Potential dry recyclables	Goal of door to door collection	Mass collected door to door	Goal of collection in ecopoints	Mass collected in ecopoints	Total goal of selective collection	Total mass collected
2017	95,542.83	7.00%	6692.95	0.58%	558.52	7.58%	7,251.47
2018	100,277.71	10.60%	10630.11	0.80%	802.27	11.40%	11,432.38
2019	102,265.35	11.70%	11965.81	1.00%	1022.72	12.70%	12,988.52
2020	104,270.36	13.00%	13556.01	1.20%	1251.32	14.20%	14,807.33
2021	106,293.09	14.30%	15200.88	1.50%	1594.50	15.80%	16,795.37
2022	108,333.10	17.00%	18417.79	1.60%	1733.44	18.60%	20,151.23
2023	110,391.32	18.40%	20313.29	1.70%	1876.77	20.10%	22,190.06
2024	112,467.05	19.70%	22157.41	1.80%	2024.54	21.50%	24,181.95
2025	114,560.91	20.90%	23944.75	2.00%	2291.36	22.90%	26,236.11
2026	116,672.77	22.10%	25786.32	2.10%	2450.28	24.20%	28,236.60
2027	118,803.00	23.10%	27445.23	2.10%	2495.02	25.20%	29,940.26
2028	120,951.62	24.20%	29272.15	2.20%	2661.10	26.40%	31933.25
2029	123,118.64	25.10%	30904.74	2.20%	2708.78	27.30%	33613.52
2030	125,304.54	25.90%	32455.94	2.30%	2882.19	28.20%	35338.12
2031	127,509.23	26.60%	33919.61	2.40%	3060.42	29.00%	36980.02
2032	129,732.46	27.20%	35289.47	2.40%	3113.78	29.60%	38403.24
2033	131,974.99	27.70%	36559.39	2.50%	3299.58	30.20%	39858.97
2034	134,236.57	28.20%	37857.11	2.50%	3356.13	30.70%	41213.24
2035	136,517.84	28.60%	39046.58	2.60%	3549.69	31.20%	42596.27
2036	138,818.19	28.80%	39982.18	2.80%	3887.16	31.60%	43869.33
2037	141,138.26	29.10%	41073.84	2.80%	3952.12	31.90%	45025.96

Source: (PMCG & DMTR, 2017c)

Table 2-7 – Waste projections per stream from 2017 to 2037. HHW (Household waste) is the sum of regular, selective, ecopoints and biowaste.

Year	MSW total	MSW total	HHW total	Regular-residual	Selective collection	Ecopoints	Biowaste	CMW	Markets	Parks	Street Cleaning
	per capita (kg/inh./day)	Quantity (tonnes/year)	Quantity (tonnes/year)	Quantity (tonnes/year)	Quantity (tonnes/year)	Quantity (tonnes/year)	Quantity (tonnes/year)	Quantity (tonnes/year)	Quantity (tonnes/year)	Quantity (tonnes/year)	Quantity (tonnes/year)
2017	0.8664	271,267.1	229,922.6	222,671.13	6692.95	558.52		27,965.9	595.6	7,754.4	5,028.7
2018	0.8707	276,704.8	234,531.5	223,099.14	10630.11	802.27		28,526.5	607.5	7,909.8	5,129.5
2019	0.8751	282,189.5	239,180.3	226,191.73	11965.81	1022.72		29,091.9	619.5	8,066.6	5,231.2
2020	0.8795	287,722.1	243,869.6	229,062.28	13556.01	1251.32		29,662.3	631.7	8,224.8	5,333.7
2021	0.8838	293,303.6	248,600.4	231,805.05	15200.88	1594.50		30,237.7	643.9	8,384.3	5,437.2
2022	0.8883	298,932.7	253,371.6	233,220.39	18417.79	1733.44		30,818.0	656.3	8,545.2	5,541.5
2023	0.8927	304,612.2	258,185.4	235,995.36	20313.29	1876.77		31,403.5	668.8	8,707.6	5,646.8
2024	0.8972	310,339.9	263,040.2	238,858.25	22157.41	2024.54		31,994.0	681.3	8,871.3	5,753.0
2025	0.9017	316,117.7	267,937.3	241,701.23	23944.75	2291.36		32,589.7	694.0	9,036.5	5,860.1
2026	0.9062	321,945.1	272,876.6	244,640.01	25786.32	2450.28		33,190.5	706.8	9,203.1	5,968.1
2027	0.9107	327,823.2	277,858.8	247,918.59	27445.23	2495.02		33,796.5	719.7	9,371.1	6,077.1
2028	0.9153	333,752.1	282,884.1	249,512.26	29272.15	2661.10	1438.57	34,407.7	732.7	9,540.6	6,187.0
2029	0.9198	339,731.7	287,952.3	240,095.55	30904.74	2708.78	14243.27	35,024.1	745.9	9,711.5	6,297.9
2030	0.9244	345,763.5	293,064.8	235,622.59	32455.94	2882.19	22104.07	35,646.0	759.1	9,883.9	6,409.7
2031	0.9290	351,847.1	298,221.1	233,255.27	33919.61	3060.42	27985.85	36,273.2	772.5	10,057.8	6,522.5
2032	0.9337	357,981.8	303,420.9	232,208.94	35289.47	3113.78	32808.70	36,905.6	785.9	10,233.2	6,636.2
2033	0.9384	364,169.8	308,665.7	231,827.86	36559.39	3299.58	36978.91	37,543.6	799.5	10,410.1	6,750.9
2034	0.9431	370,410.4	313,955.2	232,030.77	37857.11	3356.13	40711.17	38,186.9	813.2	10,588.5	6,866.6
2035	0.9478	376,705.3	319,290.7	232,561.65	39046.58	3549.69	44132.75	38,835.9	827.0	10,768.4	6,983.3
2036	0.9525	383,052.9	324,670.8	233,476.69	39982.18	3887.16	47324.75	39,490.3	841.0	10,949.9	7,100.9
2037	0.9573	389,454.8	330,097.0	234,728.62	41073.84	3952.12	50342.42	40,150.3	855.0	11,132.9	7,219.6

Source: Adapted from (PMCG & DMTR, 2017c).

2.2 LCA methodology

The goal of the study was to: (1) assess the environmental performance of different pathways for the development of MSW management in Campo Grande, and (2) to identify the contribution of different system components and waste treatment options to the overall impacts. As recommended by the European Commission (EC-JRC, 2011), the potential effects of prospective changes to the large-scale waste management systems addressed in this work were evaluated through the framework of consequential LCA. This implies system expansion in the case of multi-functionality (e.g. with substitution of by-products) and the use of marginal LCI data (as opposed to average data).

The scope definition includes the generation-based functional unit (FU) representing: the management of the total MSW generated in Campo Grande on a yearly basis between 2017 and 2037, with the quantities presented in Table 2 and compositions in Table 1. System models were elaborated in Easetech for milestone years: 2017, 2022, 2027, 2032 and 2037. The reference flow MSW should be understood as the total generated household waste and similar from small businesses, commerce and institutions, street sweeping, parks and markets. The system boundaries in this study were defined as the sum of foreground and background systems (Clift et al., 2000; EC-JRC, 2011). The foreground system comprised all waste management activities from waste generation, through treatment and recovery of materials and/or energy, while the background systems represent the surrounding economic activities (e.g. energy production, material production) that exchange flows with the waste systems. The temporal scope is 20 years, while the technological scope refers to existing waste management practices and treatment technologies. LCI process data is described in section 2.4 and consisted of primary collected data from existing system operations in 2017 complemented with literature data where information was missing, while additional scenario-based treatment options were modelled with data elaborated in Chapter 2.

The models and impact assessment were executed in Easetech, a software developed specifically for waste management LCA (Clavreul et al., 2014). The impact assessment was performed with the International Reference Life Cycle Data System (ILCD) recommended method (EC-JRC, 2010), considering 12 mid-point impact categories and global normalization factors shown in the SM (Sala et al., 2017). In the Climate Change impact category (measured as Global Warming Potential (GWP)), CO₂ that is biogenic in origin was considered climate neutral and biogenic carbon that was not emitted within 100 years was considered stored (and accounted as an avoided impact). The sensitivity of the LCA results to various uncertainty

sources was addressed by contribution analysis and scenario analysis (Bakas et al., 2018). A contribution analysis decomposes the results into process contributions, providing a quick overview of the important contributors. The scenario analysis was performed by considering different technology choices at different points in the systems assessed (described in Table 2-8).

2.3 Scenarios for future development of MSW management

2.3.1 Development of foreground systems

This study assessed two different but complementary development pathways for MSW management in Campo Grande. The first, noted as the “a series”, starts from the current practices in 2017 and follows the planned development until 2037, broadly in line with the PCS (described in section 2.1.2). The second, noted as the “b series”, comprises of additional treatment alternatives to the “a series”. Essentially, the b series does not change separate collection goals, but adds additional or different treatment perspectives for the collected streams. The main are MBT for mixed waste from regular collection, and Anaerobic Digestion (AD) for the separate biowaste stream and waste from markets. The chosen technologies were a selection of best performing options evaluated previously in Chapter 2. Table 2-8 presents the two foreground series highlighting the main waste treatment developments. Both series have a main system scenario and several scenario variations, such as for the a series: a(e) denoting a variation with energy recovery from landfill gas vs. gas flaring; and for the b series: b(i) denoting a variation where RDF is incinerated in a dedicated Waste-to-Energy (WtE) plant vs. use in cement production, and b(u) biogas upgrading vs. direct energy recovery. A variation lacking separate collection of organic waste is used in both series, denoted by a(-o).

Table 2-8 – Summary of the main foreground scenarios and variations, in the different milestone years.

Series	Year	System scenario	Scenario variations
a – Planned development	2017	- Dry separate collection sorted in an MRF and mixed waste (incl. street, parks and market waste) sanitary landfilling without gas valorization.	a(e) sanitary landfill with gas valorization
	2022 and 2027	- Dry separate collection sorted in an MRF and mixed waste (incl. street, parks and market waste) sanitary landfilling with gas valorization; parks and market waste composting .	
	2032 and 2037	- Dry separate collection sorted in an MRF and mixed waste (incl. street, parks and market waste) sanitary landfilling with gas valorization; waste from parks, markets and biowaste is composted .	a(-o) without selective biowaste collection
b – Planned development + mixed waste treatment	2017	- Dry separate collection sorted in an MRF and mixed waste sanitary landfilling with gas valorization; parks and markets composting .	
	2022 and 2027	- Dry separate collection sorted in an MRF and partial (100.000 t) mixed waste in advanced anaerobic-aerobic MBT (incl. material recovery); parks and markets composting.	b(i) RDF to dedicated WtE
	2032 and 2037	- Dry separate collection sorted in an MRF and mixed waste is extended (200.000 t) in advanced anaerobic-aerobic MBTs (incl. material recovery); parks composting; and markets and biowaste anaerobic digestion .	b(u) biogas upgraded and used as vehicle fuel b(-o) without selective biowaste collection b(i) RDF to dedicated WtE

The scenarios for the current and the future development of the waste management systems in Campo Grande considered the process flows illustrated in Fig. 2-3. The diagram shows the current practices and the different colours highlight the waste streams in relation to the treatment process. The red arrows represent the dry recyclables separately collected, the blue ones are for the biowaste as a separate stream and green arrows for the green waste, i.e. compostable material. Furthermore, black arrows demonstrate the current waste flows and grey highlights residual streams after treatment.

2.3.2 Development of background systems

The main background system considered in this study was the electricity production system affecting both system consumption and substitution of waste-recovered energy. The identification of marginal electricity suppliers was based on the method developed by Schmidt, Merciai, Thrane, and Dalgaard (2011), whereby long-term marginal technologies are defined as the technologies that display higher investment rates compared to their capital replacement rate over a given period of time. Essentially the method finds marginal electricity mixes for a given year, by a weighted average of the technologies that have increased their production from the previous reference year. The overall evolution of electricity generation in Brazil was given

by the baseline projections made by International Energy Agency – IEA (2017), illustrated in Fig. 2-4 (left). The calculated marginal electricity mixes for 2017, 2022, 2027, 2032 and 2037 are presented in Fig. 2-4 (right side). The technology processes were imported from the ecoinvent 3 database (Wernet et al., 2016) and described in Table 2-9.

Fig. 2-3 – Process flow of the systems analyzed. Notes: (1) the flow colors denote the main treatment; (2) b2022 and b2032 refer to the alternative scenarios plus the year the technology is inserted in the system.

Fig. 2-4– Electricity generation projection for Brazil according to IEA (2013) and marginal electricity mix for each milestone year with corresponding GWP factors.

Table 2-9 – Electricity mix and ecoinvent processes used for current policies trend.

Source	Ecoinvent Process	2017	2022	2027	2032	2037
Oil	"electricity production, oil; BR"	0%	0%	1.5%	0.2%	1%
Natural Gas	"electricity production, natural gas, combined cycle power plant; BR"	18.7%	14.3%	16%	17.1%	12.7%
Coal	"electricity production, hard coal; BR"	5.3%	6.1%	4.6%	0%	0%
Nuclear	"electricity production, nuclear, pressure water reactor; BR"	5.4%	4.4%	4.1%	4.6%	4%
Hidropower	"electricity production, hydro, reservoir, tropical region; BR"	0%	38.8%	48%	54.6%	56.3%
Bioenergy	"ethanol production from sugar cane; BR"	12.3%	14.3%	7.9%	4.6%	3%
Other	"electricity production, wind, 1-3MW turbine, onshore; BR"	58.3%	22.2%	18%	20%	23.1%
Renewables						

Source: (IEA, 2017).

Other background systems defined in the study address:

- RDF utilization in the industry: (1) cement production - RDF substitutes for use of petroleum coke, production and combustions was modelled as in Chapter 2; (2) industrial heat by dedicated WtE plant – RDF was assumed to substitute heat or steam from natural gas boilers. The latter assumption was based on the long-term increase of natural gas in industry, as projected by the IEA.
- Recycled materials were assumed to avoid primary production for the same material. Recycling processes were modelled based on existing literature due to the lack of LCI data of recycling systems from Brazil. However, electricity consumption was changed to the marginals developed in this work. All processes were assumed constant for the 20-year prospective period. Recycling process efficiency and substitution ratios for primary production (Rigamonti et al., 2010) are detailed in 2.3.3.
- Stabilized digestate and compost from biological treatment that is applied on agricultural soils, was assumed to substitute production and use of mineral fertilizers, as detailed in Chapter 2.

2.3.3 Scenarios – process flow diagrams (overviews directly from EASETECH)

The scenarios were designed as described above. Screenshots of each scenario and of some sub processes were taken and are shown below.

- **a series**

Fig. 2-5 shows the template for the current scenario, i.e. 2017a. The scenario contemplated sanitary landfill with flare and with energy recovery as can be observed in the figure. Furthermore, in 2017 is not considered glass recycling.

For 2022 and 2027 in a series, composting is added as treatment of markets and streets streams and glass recycling as shown in Fig. 2-6. The difference between the years is the increase on efficiency of the dry waste collected and the MRFs.

Fig. 2-7 shows the generic template for the years 2032 and 2037 from the a series. For these two years the container collection is added with a biowaste fraction collected separately.

Fig. 2-5 – “a” series of scenarios for 2017.

Fig. 2-6 – a series scenarios for 2022 and 2027.

Fig. 2-7 - a series of scenarios for 2032 and 2037.

- **b series**

For the b series scenarios there were more variations on the structures, therefore scenario 2017b is shown in Fig. 2-8.

Scenarios 2022b and 2027b are shown in Fig. 2-9 where it's first presented the MBT as treatment of the residual waste (i.e. regular collection).

Lastly, Fig. 2-10 shows scenarios 2032b and 2037b in which two MBTs, of 100,000 tonnes each, are used for the residual waste treatment.

Fig. 2-8 – 2017 scenario in b series.

Fig. 2-9 – Scenarios 2022 and 2027 in the b series.

Fig. 2-10 – 2032 and 2037 scenarios for b series.

2.4 Life Cycle Inventories (LCIs) of collection and treatment processes

2.4.1 Collection and transportation

Consumption of diesel during collection was provided by SOLURB, for currently running regular mixed waste (4.3 L.t^{-1}) and selective waste collection (11.3 L.t^{-1}). Waste collection accounted for route collection and transport to the first handling facility, and was modelled with regular (rear-loading) trucks of 10 t capacity for both types of collection. Transportation from the first handling facility to a final processing was accounted for all streams sorted for recycling, as well as for residues from sorting, composting and digestions processes to the local landfill, and RDF transport to industrial facilities. Transport was modelled with long-haul trucks of 25 t capacity for streams for recycling and RDF and trucks of 10 t for residues. Diesel consumption was 0.03 L.t^{-1} times the distance for long-haul and 0.06 L.t^{-1} times the distance for the smaller trucks (Bassi et al., 2017a). MRFs, MBTs, composting and AD sites were considered placed close to the landfill site, therefore a 5 km distance was considered for residues transport. The destinations for recycling processes were taken from the PCS and are summarized in Table 2-10.

Table 2-10– Destination and transport distance for treatment outputs.

Process outputs	Municipality	State	Distance (km)
Paper/Juice cartons/PET	Itabira	Minas Gerais	1,374
Cardboard/Fe-metal	Campo Grande	Mato Grosso do Sul	50
PE/PP	São José dos Campos	São Paulo	1,090
LDPE	Itabira	Minas Gerais	1,374
Glass	Porto Ferreira	São Paulo	855
Al-metal	São Paulo	São Paulo	1,009
Compost/Digestate	Campo Grande	Mato Grosso do Sul	10
RDF to industry	-	-	400
Residues to landfill	Campo Grande	Mato Grosso do Sul	5

Source: (PMCG & DMTR, 2017c).

2.4.2 Sanitary Landfill

Two types of sanitary landfill were modelled, i.e. without and with energy recovery from captured landfill gas. On the current landfill, Dom Antonio Barbosa II, landfill gas is flared. However, considering the short remaining lifetime of 2 years, a future extension or new landfill was assumed to include landfill gas utilization.

The landfill modules in Easetech were adapted to reflect Brazilian climate settings by changing a number of parameters (e.g. annual average temperature, precipitation, decay rates).

All settings were described in Chapter 2. Compared to this previous work, only the depth of the landfill was modified to 5 m, as provided by SOLURB.

2.4.3 Material Recovery Facility (MRF)

This MRF is managed by four of the seven cooperatives of waste pickers in Campo Grande (COOPERMARA, ATMARAS, CATA-MS and Novo Horizonte). The MRF is based mainly on manual picking (around 100 workers) assisted by basic equipment such as conveyor belts and balers. The combined yield for recovered materials represents around 55% of the waste input. In the prospective scenarios, the MRF overall efficiency was increased to 58% (2022), 63% (2027), 66% (2032) and 70% (2037), as projected in the PCS. The efficiency changes account for increased recovery of specific materials as well as the addition of glass, which is not recovered in 2017. The transfer coefficients employed for each fraction and each year are presented in Table 2-11 to Table 2-14. Consumption of electricity (15 kWh.t⁻¹), diesel (0.7 L.t⁻¹) and steel wire for bales (0.85 kg.t⁻¹) were included in the process LCI (Cimpan et al., 2016).

Table 2-11 – MRF transfer coefficients for 2017 and 2022.

Waste Fractions	Paper	Cardboard	Fe-metal	Al-metal	Glass	2D - Plastics	3D - PET	3D – PE/PP	Residues
Office Paper	90								10
Other clean Paper	90								10
Juice Cartons		95							5
Other Clean Cardboard		95							5
Food cans (tinplate/steel)			90						10
Beverage cans (Aluminium)				93					7
Clear Glass					-				100
Brown Glass					-				100
Soft Plastic						90			10
Plastic Bottles							94		6
Hard Plastics								88	2
Non-recyclable Plastic									100
Plastic products								88	2
Animal Food									100
Vegetable Food									100
Diapers, sanitary towels, tampons									100
Other non-combustibles									100
Batteries									100

Source: (Cimpan et al., 2016; PMCG & DMTR, 2017c)

Waste Fractions	Paper	Cardboard	Fe-metal	Al-metal	Glass	2D - Plastics	3D - PET	3D – PE/PP	Sorting residues
Batteries									100

Source: (Cimpan et al., 2016; PMCG & DMTR, 2017c)

Table 2-14 – MRF transfer coefficients for 2037.

Waste Fractions	Paper	Cardboard	Fe-metal	Al-metal	Glass	2D - Plastics	3D - PET	3D – PE/PP	Sorting residues
Office Paper	95								5
Other clean Paper	95								5
Juice Cartons		98							2
Other Clean Cardboard		98							2
Food cans (tinplate/steel)			93						7
Beverage cans (Aluminium)				95					5
Clear Glass					95				5
Brown Glass					80				20
Soft Plastic						93			7
Plastic Bottles							96		4
Hard Plastics								90	10
Non-recyclable Plastic									100
Plastic products								90	10
Animal Food									100
Vegetable Food									100
Diapers, sanitary towels, tampons									100
Other non-combustibles									100
Batteries									100

Source: (Cimpan et al., 2016; PMCG & DMTR, 2017c)

2.4.4 Mechanical Biological Treatment (MBT)

MBT for mixed MSW was modelled with the template developed for advanced plants in Chapter 2. The facilities consist of (1) a mechanical processing section which includes the splitting of the incoming mixed stream into wet and dry components, followed by sorting of recyclables from the dry portion with a combination of mechanical and manual sorting; and (2) a biological treatment section, which consists of dry AD followed by a stabilization of digestion residues by composting. The dry waste that remains after the sorting process is size reduced by shredding and designated as RDF. Two destinations were considered for the RDF, namely cement production facilities and dedicated WtE facilities attached to industries. The latter process was modelled with an adapted regular WtE process template, accounting for heat-only production with a boiler efficiency of 90%. The stabilized digestion residues were assumed to

be used for land reclamation purposes, namely landfill cover, due to the amount of possible contaminants.

2.4.5 Biological treatment of selective streams

Composting of waste from markets and parks was modelled based on enclosed windrows composting. Physical contamination is separated in the process and sent to the landfill, while the compost output was assumed to be used as soil amendment. Biowaste which begins to be collected in 2028, is treated by dry AD, technologically based on gas-proof box-shaped reactors, operated in batch mode at mesophilic temperatures. Digestion residues are stabilized, refined similarly to compost and used as soil amendment. Details on both composting and digestion processes can be found in Chapter 2.

3 Results

3.1 Waste flows and recycling over the study period

According to the projection adopted in the plan of selective collection of Campo Grande, in the period between 2017 and 2037, population and MSW generation are expected to increase by 30% and 44%, respectively. Fig. 2-11 illustrates through Sankey diagrams the MSW flows from generation to final treatment or disposal, for the current system (2017) and for the potential systems in the end milestone year (2037). The latter are determined by the two development pathways assessed in this work. Fig. 2-12 presents the progression of system efficiency over the 20-year period, by marking recycling rates as percentage of total generated waste. The recycling rates include both material recycling (counted by mass going to the recycling process) and biological treatment of biowaste that is separately collected (counted as mass collected).

Both figures portray the rather dismal state of recycling today, whereby more than 98% of MSW ends up in the landfill. According to the planned development in the PCS (a series), the percentage of waste mass directly landfilled should decrease to around 73% by 2037. The inclusion of residual streams from treatment brings this percentage up to 79%. In the alternative system scenario (2037b), that includes treatment of mixed MSW from regular collection by MBT, the total amount of waste that is sent to the landfill decreases to under 40%. This includes residual streams. A further 17% would constitute low quality compost that could be used to reclaim degraded land, or as daily, temporary or permanent cover for the landfill.

2017a - Baseline

2037a - Planned development

2037b - Planned development + mixed waste treatment

Fig. 2-11 – Sankey diagram with the MSW flows for 2017 (current system) and 2037 (both development scenarios).

Fig. 2-12 – Recycling rates achieved from 2017 to 2037.

3.2 Life cycle impact assessment results

Fig. 2-13 shows the impact assessment normalization step results in net PE (Person Equivalents) per environmental impact category. The net represents the sum of environmental burdens and benefits, and thus a positive net denotes an overall impact while a negative one a net saving within a category. The main system scenario development series (a and b series described in Table 2-8), are illustrated connected by lines, while scenario variations are illustrated with points. Besides the two series, a business-as-usual (BaU) scenario was added, which illustrates results if the 2017 profile of management operations is maintained throughout the period. The results values in connection to Fig. 2-13 are given in Table 2-15 and Table 2-16.

Fig. 2-13– Normalized impacts in 1000*PE throughout the years from a series and b series systems for: Climate Change (GWP), Ozone Depletion (ODP), Human Toxicity, Cancer Effects (HT, CE), Human Toxicity, non Cancer Effects (HT, non CE), Particulate Matter (PT), Photochemical Ozone Formation (POF), Terrestrial Acidification (TAD), Eutrophication Terrestrial (EPT), Eutrophication Freshwater (EPF), Eutrophication Marine (EPM), Ecotoxicity Freshwater (ECF) and Depletion of Abiotic resources, Mineral fossil and Renewable (DAMR).

Table 2-15 – Normalized net impacts in 1000*PE for all scenarios for: Climate Change (GWP), Ozone Depletion (ODP), Human Toxicity, Cancer Effects (HT, CE), Human Toxicity, non Cancer Effects (HT, non CE), Particulate Matter (PT), Photochemical Ozone Formation (POF), Terrestrial Acidification (TAD), Eutrophication Terrestrial (EPT), Eutrophication Freshwater (EPF), Eutrophication Marine (EPM), Ecotoxicity Freshwater (ECF) and Depletion of Abiotic resources, Mineral fossil and Renewable (DAMR)

Scenario	GWP	ODP	HT, CE	HT, non CE	PT	POF	TAD	EPT	EPF	EPM	ECF	DAMR
2017a (BaU)	4.42	2.99	2.90	10.34	0.44	2.20	0.50	1.01	1.15	1.23	4.4904	-0.37
2017a(e)	3.84	3.29	-6.23	-0.04	-0.77	3.31	0.87	2.29	0.66	1.90	-3.5195	-1.48
2017b	3.83	3.17	0.06	41.53	-0.71	3.29	0.89	2.32	0.29	1.91	-2.2533	-1.44
2022a	3.02	2.45	-2.46	46.80	-1.40	3.14	0.47	2.33	0.36	1.99	0.0142	-2.20
2022b	-3.23	0.36	-11.62	56.19	-2.92	3.25	-1.31	2.07	1.14	2.65	-0.9251	-2.88
2022b(i)	-1.60	0.36	-13.34	51.83	-2.48	3.69	-0.35	2.51	1.15	2.89	-0.91	-3.13
2022BaU	4,87	3,30	3,20	11,40	0,49	2,43	0,55	1,11	1,27	1,36	4,95	-0,40
2027a	3.09	2.11	-8.80	52.20	-2.25	3.43	0.14	2.53	0.07	2.17	-2.1331	-3.71
2027b	-3.57	0.05	-19.04	59.56	-4.03	3.27	-1.72	2.11	0.81	2.77	-3.4931	-4.45
2027b(i)	-1.94	0.05	-20.83	54.72	-3.59	3.71	-0.76	2.55	0.82	3.02	-3.50	-4.71
2027BaU	5,34	3,62	3,51	12,50	0,53	2,66	0,60	1,22	1,39	1,49	5,43	-0,44
2032a	1.69	1.28	-19.27	119.36	-2.49	3.34	0.09	2.77	-1.60	2.51	-0.6539	-4.52
2032a(-o)	3.11	1.89	-11.19	58.47	-2.67	3.67	0.05	2.72	0.15	2.39	-2.70	-4.59
2032b	-12.23	-2.83	-46.21	128.22	-7.01	2.22	-4.27	1.68	-0.46	3.56	-5.7934	-6.29
2032b(i)	-8.83	-2.84	-49.91	118.72	-6.10	3.12	-2.28	2.57	-0.46	4.06	-5.80	-6.82
2032b(u)	-14.71	-3.00	-53.19	127.75	-9.01	-2.20	-6.08	-0.23	-1.09	2.44	-5.6006	-6.11
2032b(-o)	-10.41	-2.18	-37.34	68.09	-7.14	2.60	-4.49	1.37	1.32	3.09	-7.15	-6.26
2032BaU	5,83	3,95	3,83	13,65	0,58	2,91	0,66	1,33	1,52	1,62	5,93	-0,48
2037a	0.86	0.88	-30.23	154.71	-3.49	3.25	-0.26	2.83	-2.92	2.68	-2.1307	-5.96
2037a(-o)	3.05	1.80	-17.84	61.41	-3.77	3.76	-0.34	2.76	-0.23	2.49	-5.35	-6.07
2037b	-13.23	-3.20	-57.89	163.86	-8.07	2.06	-4.56	1.83	-1.81	3.83	-7.5152	-7.76
2037b(i)	-9.79	-3.20	-61.70	153.43	-7.15	2.97	-2.55	2.73	-1.80	4.34	-7.50	-8.30
2037b(u)	-16.07	-3.38	-65.62	163.13	-10.19	-2.76	-6.45	-0.16	-2.53	2.65	-6.9281	-7.54
2037b(-o)	-10.46	-2.19	-44.27	71.55	-8.27	2.65	-4.89	1.36	0.92	3.12	-9.57	-7.71
2037BaU	6,35	4,30	4,17	14,85	0,64	3,16	0,72	1,44	1,65	1,77	6,45	-0,53

Table 2-16 - Characterized net LCA results for all scenarios.

Scenarios	GWP (kg CO ₂ eq.)	ODP (kg FC-11 eq.)	HT, CE (CTUh)	HT, non CE (CTUh)	PT (kg PM _{2.5} eq.)	POF (kg NMVOC eq.)	TAD (mol + eq.)	EPT (mol N eq.)	EPF (kg P eq.)	EPM (kg N)	ECF (CTUe)	DAMR (kg Sb eq.)
2017a (BaU)	37127977.63	70.07	0.11	4.91	2243.96	89399.18	27755.38	178083.15	845.14	34812.99	52987227.19	-70.77
2017a(e)	32277897.91	76.93	-0.24	-0.02	-3923.00	134544.21	48130.01	406212.24	484.30	53777.00	-41530057.75	-285.41
2017b	32160056.81	74.25	0.00	19.73	-3583.59	133468.83	49493.01	410422.11	214.25	54127.64	-26588899.90	-277.90
2022a	25406381.74	57.24	-0.09	22.23	-7121.79	127531.90	26348.07	412548.20	264.83	56276.96	167256.67	-423.83
2022b	-27151056.61	8.41	-0.45	26.69	-14810.39	131818.23	-72579.10	366462.38	839.22	75002.78	-10916626.94	-555.44
2022b(i)	-13415085.98	8.39	-0.51	24.62	-12558.03	149754.71	-19312.62	444083.26	843.84	81908.64	-10794168.04	-603.98
2022BaU	40914524.36	77.22	0.12	5.41	2472.81	98516.68	30586.05	196245.20	931.33	38363.44	58391202.13	-77.99
2027a	25937328.83	49.33	-0.34	24.79	-11386.93	139184.16	7604.03	447191.64	53.91	61407.61	-25170270.74	-715.59
2027b	-30006909.84	1.10	-0.73	28.29	-20446.59	132848.34	-95377.79	374008.10	596.87	78489.32	-41218884.16	-859.59
2027b(i)	-16308341.59	1.08	-0.80	25.99	-18226.54	150610.18	-42402.00	451058.19	600.13	85334.18	-41278019.67	-908.37
2027BaU	44868746.14	84.68	0.14	5.94	2711.80	108037.91	33542.06	215211.51	1021.34	42071.11	64034473.18	-85.53
2032a	14192780.71	30.00	-0.74	56.69	-12612.96	135634.43	4982.68	490898.84	-1175.23	71167.03	-7715628.90	-871.53
2032a(-o)	26088589.43	44.11	-0.43	27.77	-13529.39	148948.17	2585.31	482290.44	110.80	67655.95	-31864632.19	-885.15
2032b	-102705246.80	-66.33	-1.78	60.91	-35542.64	90204.92	-236880.27	297034.77	-341.00	100721.01	-68361676.30	-1213.90
2032b(i)	-74175655.33	-66.38	-1.92	56.39	-30908.63	126671.85	-126609.33	455396.38	-334.40	114778.77	-68447194.72	-1316.32
2032b (u)	-123545172.69	-70.10	-2.05	60.68	-45663.37	-89500.15	-337386.87	-41228.15	-800.65	68923.13	-66086572.09	-1178.76
2032b(-o)	-87479158.36	-50.91	-1.44	32.34	-36190.92	105731.71	-249059.90	242852.65	966.90	87478.03	-84337562.34	-1207.69
2032BaU	48996514.65	92.47	0.15	6.48	2961.27	117977.02	36627.83	235010.19	1115.30	45941.50	69925408.11	-93.40
2037a	7248761.63	20.53	-1.16	73.49	-17707.13	131983.38	-14505.74	500759.47	-2142.20	75840.67	-25141848.10	-1149.98
2037a(-o)	25584995.46	42.18	-0.69	29.17	-19098.65	152730.47	-18659.21	488264.57	-166.76	70539.41	-63101206.26	-1171.19
2037b	-111171849.67	-74.90	-2.23	77.83	-40930.09	83735.81	-253201.84	323240.34	-1331.38	108385.36	-88679894.46	-1497.27
2037b(i)	-82259178.30	-74.95	-2.38	72.88	-36235.10	120589.66	-141503.71	483326.80	-1319.38	122720.95	-88475012.14	-1601.15
2037b (u)	-134995496.44	-79.15	-2.53	77.48	-51687.34	-111954.25	-357789.95	-28910.00	-1857.45	75059.36	-81752025.89	-1455.53
2037b(-o)	-87853441.36	-51.25	-1.70	33.99	-41926.38	107514.32	-271556.60	240639.38	674.52	88161.38	-112950373.73	-1487.81
2037BaU	53304177.68	100.60	0.16	7.05	3221.62	128349.30	39848.05	255671.78	1213.35	49980.57	76073105.88	-101.61

3.2.1 Evolution of impacts over the period

At a first glance, it can be observed that both development pathways lead to a decrease in environmental impact over time, in most impact categories. There are, however, exemptions that will be analysed in the following.

Net savings in GWP were not achieved in any of the “a series” scenarios, however the impacts decrease by 87% from 2017 to 2037, even though the waste generation amount is projected to increase by almost 50%. The relatively conservative separate collection and recycling goals in the planned development pathway of the PCS, lead to savings due to avoided materials production, but cannot compensate the impacts related to the large amount of waste that is landfilled. The “b series” transitions to net climate savings already by 2022 and savings increase substantially by 2037. The gap between the two development pathways is explained by high savings due to the material recovery for recycling and utilization of RDF as substitution of coke in cement production, both associated with the MBT process.

The development over the period observed for GWP, is similar for a number of other categories, namely ODP, HT, CE, PT, TAD and DAMR.

In contrast, HT, non CE is an impact category where burdens increase substantially and similarly in both development pathways. This was tracked to the metals present in the compost (such as zinc and lead), mainly originating in plastic products and other non-combustibles, but also present in fine fractions of park waste (e.g. leaves, grass). For EPT combustion processes (such as biogas combustion, collection and transportation) are the biggest contributors, mainly from NO_x emitted. The difference between the two development pathways and the better performance in the “b series” is due to reductions in the amount of waste that is directly landfilled. Burdens also increased in EPM over time. This was connected largely to landfilling and waste collection processes. The impact is higher in the “b series” due to land reclamation using the compost-like output from MBT. The main contributing emissions are nitrate leaching to water and nitrogen oxides emissions from collection trucks to air. Lastly, burdens decreased in both development pathways with regard to EPF, but were consistently higher for the “b series”. The processes determining this decrease were land reclamation using the compost-like output from MBT, and, rather surprisingly, recycling of LDPE plastics and cardboard. If compost-like output from MBT are applied solely as landfill cover, their potential for eutrophication is in reality expected to be minimal, due to treatment of leachate and runoff from the landfill site.

3.2.2 Scenario variations

The immediate change from a sanitary landfill with gas flaring to a sanitary landfill with energy recovery, improved the performance of the existing waste management system (2017a(e)) in more than half of the assessed environmental impact categories. This included GWP, HT, CE and HT, non CE, PT, EPF, ECF and DAMR.

The source separation of biodegradable waste, especially food waste, and its treatment either by composting or AD, was shown to have a specific high importance for decreasing a large number of potential environmental impacts. The (-o) scenarios represent system variations where food waste from households is not separated, and therefore facilitate illustrating the significance of this system choice in Fig. 2-13.

The utilization of biogas from AD for electricity production did not result in significant savings due to the relative low burdens of marginal electricity production in Brazil over the period. Upgrading of biogas and utilization as vehicle fuel, showed significantly higher benefits especially in GWP, PT, POF, TAD and EPT. Except for GWP, benefits in the other categories are explained by large amounts of mainly NO_x, SO₂ (Sulfur dioxide) and Nitrate (NO₃⁻) that are avoided.

3.3 Specific contributions to climate change

The characterization step results for all scenario variations are illustrated in Fig. 2-14, both in absolute scenario values and per tonne of waste generated in the five milestone years. The result values can also be found in Table 2-17 and Table 2-18.

Table 2-17 – Process contribution, full functional unit – Characterization LCA results for GWP (kg CO₂eq.).

Scenarios	Collection	MRF	Recycling emissions	Avoided material production	Landfill	Composting	MBT	Energy savings	RDF combustion	Avoided coke	Avoided fuel	Anaerobic Digestion	Avoided fertilizer	Land reclamation	Net
2017a	3680.48	56.46	2088.13	-6600.68	37903.58										37127.98
2017a(e)	3680.48	56.46	2088.13	-6600.68	36891.29			-3837.79							32277.90
2017b	3575.78	56.46	2088.13	-6600.68	36777.24	290.14		-3746.07					-280.93		32160.07
2022a	4193.61	162.72	6415.62	-19258.88	38402.36	344.52		-4535.32					-318.24		25406.38
2022b	4193.92	162.72	12806.32	-43039.55	20776.88	344.52	2685.60	-5618.40	14818.62	-36701.37		1708.07	-318.24	1029.85	-27151.06
2022b(i)	4193.92	162.72	12806.32	-43039.55	20776.88	344.52	2685.60	-28993.70	15228.52			1708.07	-318.24	1029.85	-13415.09
2027a	4765.55	234.86	11160.78	-31916.35	46069.85	369.91		-4398.27					-349.00		25937.33
2027b	4765.55	234.86	17186.37	-55007.10	24681.88	369.91	2557.50	-5470.95	14809.07	-36572.78		1736.43	-349.00	1051.36	-30006.91
2027b(i)	4765.55	234.86	17186.37	-55007.10	24681.88	369.91	2557.50	-28734.64	15198.56			1736.43	-349.00	1051.36	-16308.34
2032a	5671.32	258.87	12875.83	-40936.23	37653.39	1913.77		-1931.83					-1312.34		14192.78
2032a(-o)	4897.54	258.87	12875.83	-40936.23	51191.60	362.65		-2180.56					-381.11		26088.59
2032b	5689.85	258.87	23417.19	-88604.22	-3492.47	327.69	3937.40	-4730.25	31727.44	-76534.63		4954.53	-1633.29	1976.64	-102705.25
2032b(i)	5689.85	258.87	23417.19	-88604.22	-3492.47	327.69	3937.40	-53530.97	32523.13			4954.53	-1633.29	1976.64	-74175.66
2032b (u)	5689.85	258.87	23417.19	-88604.22	-3492.47	327.69	3937.40	-600.41	31727.44	-76534.63	-24967.64	4952.41	-1633.29	1976.64	-123545.17
2032b(-o)	4897.54	258.87	23417.19	-88604.22	12115.66	362.65	3937.40	-3958.71	31727.44	-76534.63		3306.13	-381.11	1976.64	-87479.16
2037a	6374.15	296.96	16378.48	-50680.13	35645.73	2743.79		-1666.71					-1843.51		7248.76
2037a(-o)	5186.84	296.96	16378.48	-50680.13	56417.12	388.61		-1988.27					-414.61		25585.00
2037b	6394.31	296.96	26663.49	-98336.69	-5461.74	351.00	3780.59	-4830.99	32231.81	-77588.12		5731.59	-2332.60	1928.54	-111171.85
2037b(i)	6394.31	296.96	26663.49	-98336.69	-5461.74	351.00	3780.59	-54305.46	33030.82			5731.59	-2332.60	1928.54	-82259.18
2037b (u)	6394.31	296.96	26663.49	-98336.69	-5461.74	351.00	3780.59	-541.01	32231.81	-77588.12	-28111.24	5729.20	-2332.60	1928.54	-134995.50
2037b(-o)	5186.84	296.96	26663.49	-98336.69	18475.66	388.61	3780.59	-3711.34	32231.81	-77588.12		3244.83	-414.61	1928.54	-87853.44

Table 2-18 - Process contribution, functional unit normalized to 1 tonne – Characterization LCA results for GWP (kg CO₂eq.). Red suggests the worst overall performing scenario and green the best overall performing scenario.

Scenarios	Collection	MRF	Recycling emissions	Avoided materials production	Landfill	Composting	MBT	Energy savings	RDF combustion	Avoided coke	Avoided fuel	Anaerobic Digestion	Avoided fertilizer	Land reclamation	Net
2017a	13.57	0.21	7.70	-24.33	139.73										136.87
2017a(e)	13.57	0.21	7.70	-24.33	136.00			-14.15							118.99
2017b	13.18	0.21	7.70	-24.33	135.58	1.07		-13.81					-1.04		118.55
2022a	14.03	0.54	21.46	-64.43	128.46	1.15		-15.17					-1.06		84.99
2022b	14.03	0.54	42.84	-143.98	69.50	1.15	8.98	-18.79	49.57	-122.77		5.71	-1.06	3.45	-90.83
2022b(i)	14.03	0.54	42.84	-143.98	69.50	1.15	8.98	-96.99	50.94			5.71	-1.06	3.45	-44.88
2027a	14.54	0.72	34.05	-97.36	140.53	1.13		-13.42					-1.06		79.12
2027b	14.54	0.72	52.43	-167.80	75.29	1.13	7.80	-16.69	45.17	-111.56		5.30	-1.06	3.21	-91.53
2027b(i)	14.54	0.72	52.43	-167.80	75.29	1.13	7.80	-87.65	46.36			5.30	-1.06	3.21	-49.75
2032a	15.84	0.72	35.97	-114.35	105.18	5.35	0.00	-5.40	0.00	0.00	0.00	0.00	-3.67	0.00	39.65
2032a(-o)	13.68	0.72	35.97	-114.35	143.00	1.01	0.00	-6.09	0.00	0.00	0.00	0.00	-1.06	0.00	72.88
2032b	15.89	0.72	65.41	-247.51	-9.76	0.92	11.00	-13.21	88.63	-213.79	0.00	13.84	-4.56	5.52	-286.90
2032b(i)	15.89	0.72	65.41	-247.51	-9.76	0.92	11.00	-149.54	90.85	0.00	0.00	13.84	-4.56	5.52	-207.21
2032b (u)	15.89	0.72	65.41	-247.51	-9.76	0.92	11.00	-1.68	88.63	-213.79	-69.75	13.83	-4.56	5.52	-345.12
2032b(-o)	13.68	0.72	65.41	-247.51	33.84	1.01	11.00	-11.06	88.63	-213.79	0.00	9.24	-1.06	5.52	-244.37
2037a	16.37	0.76	42.05	-130.13	91.53	7.05	0.00	-4.28	0.00	0.00	0.00	0.00	-4.73	0.00	18.61
2037a(-o)	13.32	0.76	42.05	-130.13	144.86	1.00	0.00	-5.11	0.00	0.00	0.00	0.00	-1.06	0.00	65.69
2037b	16.42	0.76	68.46	-252.50	-14.02	0.90	9.71	-12.40	82.76	-199.22	0.00	14.72	-5.99	4.95	-285.46
2037b(i)	16.42	0.76	68.46	-252.50	-14.02	0.90	9.71	-139.44	84.81	0.00	0.00	14.72	-5.99	4.95	-211.22
2037b (u)	16.42	0.76	68.46	-252.50	-14.02	0.90	9.71	-1.39	82.76	-199.22	-72.18	14.71	-5.99	4.95	-346.63
2037b(-o)	13.32	0.76	68.46	-252.50	47.44	1.00	9.71	-9.53	82.76	-199.22	0.00	8.33	-1.06	4.95	-225.58

Fig. 2-14 – Characterized GWP impacts in absolute values and per tonne of waste generated. Note: Collection represents the sum of emissions from regular and selective; Landfill represents the net of emissions minus carbon storage; Recycling represents the net of recycling emissions minus savings of primary production; Energy savings represents the sum of all energy saved in the system (e.g. from landfill gas and steam in the industry).

Landfill GHG emissions remained the main contributor to climate burdens in all “a series” scenarios. In absolute terms, landfill emissions decrease only by around 5% between 2017a and 2037a. However, if biowaste would not be collected separately (2037a(-o)), there would be an overall increase in emissions by almost 50% over the same period. The results are more optimistic when accounting development of impacts per tonne of waste generated. Between 2017a and 2037a, GHG emissions decreased by 35%, while if biowaste would not be collected separately (2037a(-o)), there is only a small overall increase of 4%. A more interesting prospect is put forward by results from the “b series”. With the installation of a second MBT, more than two thirds of mixed waste from regular collection are treated. When combined with the selective collection of biowaste (2032b, 2037b), this results in a drastic reduction of food waste going to the landfill, which in turn renders the overall net impact of landfilling to become negative (i.e. a saving). This is due to the presence of hardly degradable carbon in other waste than food waste, which will be stored in the landfill.

The upgrading of the current landfill (2017), from flaring of captured landfill gas to utilization for electricity production, would contribute with energy savings equivalent to 10% of the current landfill emissions. These savings are also equivalent to 50% of the climate savings brought by recycling and avoided materials production in 2017.

Collection represents in all scenarios 7%-10% of the total climate burden and this remained constant over the period. However, in absolute terms the burden would almost double between 2017 and 2037. The long-distance transport of the RDF (400 km) contributes around 6% of the total climate change burden of the process (i.e. sum of transport and direct RDF combustion emissions). In the case of recycling processes, long-distance transport contributes in total between 18% and 22% of the total climate change burden of the processes. However, in categories like POF, TAD, EPT and EPM the contribution can be much higher, between 40% and 50%.

Composting of parks and markets waste, and later biowaste in the “a series”, contributes with a net burden even after subtracting the savings brought by avoided mineral fertilizer. This net burden is quite small compared to emissions if this organic waste is instead landfilled. This can clearly be seen when comparing 2032a with 2032a(-o) and 2037a with 2037a(-o) in Fig. 8. Dry digestion, employed in the “b series” in both MBT and for biowaste, results in net savings, but these are relatively small (barely visible in Fig. 2-14) due to the low impact of background energy production in Brazil over the period. Biogas upgrading and utilization as vehicle fuel in large commercial vehicles (e.g. buses and trucks) results in much higher savings, if it avoids diesel use, as modelled in this study.

In the “a series”, recycling and avoided material production accounts for the majority of climate benefits over the period, with energy savings connected to the landfill decrease in share substantially (5% in 2037). Absolute savings due to recycling should triple between 2017a and 2022a, and become seven times higher at the end of the period assessed. In the “b series” benefits connected to recycling double compared to the equivalent “a series” scenarios. Recycling emissions contributing to climate change, which account for long distance transport and actual materials reprocessing, are on average three times smaller than the benefits from avoided primary materials production. However, this does not apply across the board to other environmental impacts. For other categories, savings are smaller, only 1.2-2 times bigger than the recycling burdens (e.g. PT, POF, TAD and all eutrophication impact categories).

Direct emissions from RDF combustion in the “b series” dominate the climate burdens in 2032 and 2037. However, savings related to avoided production and utilization of coal coke in cement kilns (b scenarios), as well as avoided natural gas boilers in industry (b(i)), are much higher in both cases.

4 Discussion

The present work assessed the environmental performance of two complementary pathways for the development of MSW management in Campo Grande over the next 20 years. While one pathway is based primarily on the municipality's official implementation strategy (the PCS), the second was constructed with the intention to explore the upper range of potential environmental benefits by complementing separate collection with a parallel development of mixed waste treatment infrastructure. Despite the significant range between the results for the two pathways, the b series can still be regarded as conservative, as we intended to present a scenario that can reasonably be implemented in Campo Grande. The inclusion of the BaU scenario, whereby there is no significant future change in the current waste management system, was not expressly in focus. Nevertheless, a no change scenario was tested, and revealed as expected a gradual increase in environmental burdens in line with the increase in waste generation (44% over the period). Therefore, our results suggest that even the implementation of the PCS with or without selective collection of biowaste (a(-o) in Fig. 2-14), would result in a substantial reduction in the climate impact of MSW management. This applies across most environmental impacts.

The technological option of WtE by incineration for direct treatment of mixed MSW was not included in the “b series” as a result of previous research that determined little benefits from its application in Brazil. Firstly, WtE is an option that would require Brazilian municipalities to dispose of much higher budgets for waste management (Leme et al., 2014). Secondly, compared to Europe or Asia, WtE does not bring significant environmental savings to the system by energy production, due to the big share of renewable sources in the electricity matrix of Brazil (Goulart Coelho & Lange, 2018; Liikanen et al., 2018; P. D. M. Lima et al., 2018; F. R. Soares, 2017). In addition, from a social perspective, WtE does not create work places in the same way as MBT. WtE requires relatively few specialized operator positions, whereas MBT can be labour intensive and could incorporate many more low skilled workers (sorting positions), as well as specialized positions to operate the various mechanical sorting and biological treatment operations.

In the case of MBT, which dominates the results of the “b series”, it is important to stress that environmental benefits are dependent on two main aspects, namely process efficiency and substitution factors in relation to process outputs when utilized further in the economy. The latter applies especially to materials that are recovered for recycling. The effect of process efficiency was tested in Chapter 2, where both simple and advanced MBTs were modelled.

Result revealed that except for the resource depletion category, there are minor trade-offs between basic and advanced MBTs, as long as materials that are potentially recyclable and are not sorted end up in RDF, whereby they are used for energy production instead. Sorting efficiencies (transfer coefficients, kg sorted/kg input material) for the MBT in this study included 30%/40% for paper/cardboard, 80% for ferrous metals, 60% for aluminium and 60% for plastics. These efficiencies are on the higher end of values reported in literature (e.g. Montejo et al. (2013), Cimpan et al. (2015)) but not unreasonable. In relation to substitution, we consider the cumulative effect of final processing yield (e.g. aluminium waste re-melting) and market-based substitution factors. In the case of problematic materials such as plastics, the result is $0.75 \times 0.81 = 0.61$, meaning that 1 kg of sorted waste plastics potentially replaces 0.61 kg of primary produced plastics. The effect of using lower substitution factors is an almost linear decrease in benefits of recycling in most impact categories, but does not change scenario ranking (within a and b series or between series).

RDF utilization in cement production has been widely implemented in Europe, but not without challenges (Cimpan et al., 2015; de Beer et al., 2017; Gallardo et al., 2014). Although Brazil has a large cement production industry, there is little to no experience with RDF streams from MSW. For this to change, and to ensure that this option of RDF utilization will not cause more environmental harm than benefits, the implementation and strict compliance with some quality standards would be necessary (Velis et al., 2010). RDF could be used instead in dedicated boilers, essentially WtE plants that are connected to other industrial production processes. In this case, quality would be less important, however environmental benefits would depend on substituting heat or steam produced by burning fossil fuels.

4.1 Further limitations and uncertainty

The present environmental assessment was built on the basis of comprehensive primary data, including most of the data that described the systems, such as waste flows, collection and some treatment processes. Remaining treatment processes were modified to be geographically representative, following an approach demonstrated by Henriksen et al. (2018) for landfilling. The combination of local data and context specific process modelling should reduce uncertainty in the results (see for example Ripa et al. (2017)). Similarly, some background systems were described by developments in Brazil for background sectors, e.g. the energy system. However, other LCIs could not be based on local primary data. Notably among these are processes for material recycling, which were based on inventories for processes mostly documented in Europe, where the authors only changed electricity inputs to that produced in Brazil. In general,

there is a need to produce more LCIs that represent the technological and socio-economic characteristics of Brazil, and more broadly also for other developing countries.

Another area that needs to be addressed concerns datasets for physico-chemical properties of waste fractions. Most studies to date, including the present work, are not based on analyses of Brazilian waste. The elemental composition for all material fractions (in the Easetech library) are based on analysis of waste collected in Denmark. Variations in composition and physico-chemical properties can alter LCA results, sometimes significantly as demonstrated by Bisinella et al. (2017). Including this uncertainty is likely to change absolute values in our results but will not change ranking between scenarios. Our results showed, for example, that a significant presence of zinc in the matrix of certain garden and park waste fractions contributed significantly to burdens in human toxicity (HT, non CE) through the application of compost. As we cannot validate this result for the moment, it is a general indicator that the presence of heavy metals in compost is of concern, and should be tested and monitored on the relevant waste and compost streams.

Finally, the overall gravimetric composition of MSW generated by households was not changed over the 20 year period. This could be considered a weakness, but the reason for proceeding this way was that the baseline composition, unlike typical compositions for regions in developing countries, already displayed quite a low share of biodegradable organics (46%) and high shares of plastics (21%) and paper-cardboard (11%), which is typical of high-income countries. A further decrease in organics over time would result in lower impacts related to waste degradation in landfills, while an equivalent increase in dry waste fractions would probably benefit recycling and energy recovery through RDF.

4.2 Barriers to sustainable MSW management

Since 2012, selective collection for recyclable materials has been running in Campo Grande, and it covers today more than 40% of the urban population. However, actual participation in the scheme is quite low, which explains the current amounts collected. The PCS, in its strategic planning, follows a cautious, conservative approach with regard to milestones and goals, which reflect that the municipality has been taking relatively small steps towards a more sustainable waste management system in the past few years. Even so, similar to many other municipalities of Brazil, there is a risk that the PCS will not come to fruition, at least in terms of expected performance.

Both barriers and potential solutions to an efficient development towards sustainable solid waste management in Brazil are increasingly well understood (Conke, 2018; Maiello,

Lucia, De, Britto, & Freitas Valle, 2018). It is crucial for the local government to consider them, in order to reap the environmental benefits indicated by this work, as well as associated socio-economic benefits. The success of local policies on waste recycling implemented by local governments is dependent on households' acceptance and change in behaviour, just as much as it is on the behaviour of local representatives, and their continued commitment to modify current practices (Conke, 2018). Moreover, success is dependent also on commitment to quality of service from all actors in the management chain, including collectors, the cooperatives responsible for sorting and companies performing other waste treatment. Both participation by households and delivery of quality service by actors involved, need to be incentivized through targeted actions.

One of the main barrier found by researchers in Brazilian recycling programs is the lack of any kind of tangible return for citizens recycling behaviour. They are typically not informed of what happens to the waste they sort, and unlike other services such as energy or water consumption, for waste services there is no association between behaviour and cost to access the service. The lack of adequate waste fees affects all subsequent actors, in the form of inadequate budgets for collection, sorting and treatment infrastructure. Additionally, selective collection recyclables across Brazil display large amounts of contamination, and this has been connected to a lack of proper communication of the materials covered by these schemes. All this is in contrast with a general public acceptance of recycling and its benefits in Brazil, and this suggests that there is great potential for success, given a proper and committed approach from everyone involved.

5 Conclusions

With a projected population increase of 30% and MSW generation increase of 44% over the next 20 years, environmental burdens related to waste management in Campo Grande, Brazil will proportionally grow given lack of changes in management practices. Based on the present evaluation of two prospective development pathways where management practices are gradually changed, we can conclude the following:

(Planned development pathway): A gradual increase in separate (selective) collection for recyclables balanced or even decreased negative environmental impacts in several impact categories over time. The addition of biodegradable organics to separate collection further decreased impacts in some categories (e.g. Global Warming Potential) but pointed to potential burdens in some toxicity categories (e.g. Freshwater Ecotoxicity) due to compost application in agriculture.

(Planned development + mixed MSW treatment): Mixed waste treatment by MBT, entailing sorting of several recyclables and production of RDF to be used in cement production, showed a high potential for positive environmental externalities, given the assumption that these process outputs can displace primary materials and fossil fuels respectively in the wider economy. Further technology changes, such as anaerobic digestion of separately collected biowaste and organic fractions sorted in MBT, have minimum positive effect if biogas is used directly for production of energy (given the low impact of electricity production in Brazil). Biogas upgrading would be preferred on the condition that it can replace fossil fuels in heavy transport.

References

“All references are presented in the end of this document.”

CHAPTER 4 - GENERAL CONCLUSIONS

The environmental impacts of different waste technologies and streams, for a generic case study of Brazilian conditions and specific for Campo Grande/MS, have been assessed through consequential life cycle assessment. The steps developed generated data and information to support and contribute to decision-making regarding waste management systems in the country.

From the analysis, it became very clear that the waste disposal in dumps and controlled landfills have the highest environmental burdens when compared to sanitary landfills (with and without energy recovery). This is explained by the lack of treatment of the gas and leachate. Furthermore, incineration (WtE plant) presented high burdens in some categories due to the combustion process, even though the savings in electricity substitution were significant, it is not the most beneficial alternative to the Brazilian reality, due to the low-carbon energy matrix.

The content of chapters 2 and 3 presented in this thesis are complementary studies with the results aligned with each other. Since WtE was not considered beneficial, this was not assessed for the case study in Campo Grande, on the other hand the other studied alternatives followed the same patterns in relation to environmental savings or burdens. For example, as the amounts of waste going to recycling/recovery increases and the fractions destined to landfills decreases, the environmental performance improves considerably. Windrows composting presented high emissions when compared to enclosed composting, which may not seem like a very advantageous option, however due to its simplicity and the deviation of the biowaste fraction from the landfill, it is still an appealing choice to start with.

When more robust and advanced alternatives are added to the scenarios, such as AD and MBT, the improvements on environmental performance are remarkable. MBT, in its both arrangements (simple and advanced) contributed to different sectors, such as recovery, fossil fuel usage in the cement industry, fossil fuel burned in vehicle systems, etc. This is a new type of technology to the Brazilian standards, but it has been employed progressively in developed and developing countries and it could be further explored due to the potential in the widespread cement production in the country. Furthermore, the lack of public participation on selective collection schemes, could be partially and temporarily solved with a mixed waste MBT, until the population is more familiar with the benefits of source separation and the better quality of MBT outputs once it receives “clean” waste as input.

Considering that climate change is most of the time the main focus of discussions, in this analysis the biggest burden contributor to the category was the landfill gas from the dumps and

the biggest savings were achieved from the avoided coke replaced by RDF. It is important to emphasize that the environmental performance of waste management scenarios should be considered by the Brazilian decision-makers, not only the economic aspects as it happens nowadays. Some of the scenarios assessed, especially the ones with energy recovery could also improve the economic advantages of a cleaner waste management system, however, the sustainability of the systems should be aimed, considering the environmental and social aspects as well. Therefore, these other aspects should be further assessed in other researches.

In a societal perspective, in Campo Grande it was verified that if the population does not contribute to the already existing selective collection, indicating that, whichever system is implemented will not work. The results showed that the projections of public participation are not enough to bring the system down to net savings even in 20 years. Therefore, more drastic measures need to be taken, but not only from one side (authorities) but the entire population has to contribute, which calls for environmental education (not only in Campo Grande) concerning solid waste and sustainable environment.

This doctoral research showed an overview of the possible alternatives for MSW management in Brazilian municipalities. Further than that, it brings valuable data on not only current but future prospects in the waste management sector. Chapters 2 and 3 presented here are papers that have been published in high quality peer reviewed journals, which we believe will serve as guide to other researchers from other regions/municipalities in the country and other developing countries, in order to assess specificities to define technologies that are more adequate to each situation. It is recommended that more case studies in different areas of Brazil are developed, and that the economic and societal aspects of the alternatives should be evaluated aiming the sustainability of the systems.

Lastly, this work received great collaboration from co-authors and reviewers to bring advances in the methodological delineation and discussion aspects in the field of life cycle assessment of waste management systems, to support decision-making in Brazil. Confidently, it will serve as support for other researchers and decision-makers aiming at improving the environmental performance of waste management systems in the country.

REFERENCES

- ABNT. (2016). NBR ISO 14040 - Gestão ambiental - Avaliação do ciclo de vida - Princípios e estrutura. Rio de Janeiro.
- ABRELPE. (2013). *Atlas brasileiro de emissões de GEE e Potencial Energético na Destinação de Resíduos Sólidos*. São Paulo, SP, Brasil. Retrieved from http://www.abrelpe.org.br/arquivos/atlas_portugues_2013.pdf
- ABRELPE. (2017). *Panorama dos resíduos sólidos no Brasil 2016*. <https://doi.org/ISSN 2179-8303>
- Alam, P., & Ahmade, K. (2013). Impact of Solid Waste on Health and the Environment. *International Journal of Sustainable Development and ...*, 2(1), 165–168. Retrieved from http://irnet.sg/irnet_journal/IJSDGE/IJSDGE_doc/IJSDGE_V2I1,2_papers/31.pdf
- Alcantara, A. J. de O. (2010). *Composição gravimétrica dos resíduos sólidos urbanos e caracterização química do solo da área de disposição final do município de Cáceres-MT*. Universidade do Estado do Mato Grosso. Retrieved from <http://www.unemat.br/prppg/ppgca/teses/2010/02.pdf>
- Alfaia, R. G. de S. M., Costa, A. M., & Campos, J. C. (2017). Municipal solid waste in Brazil: A review. *Waste Management & Research*, 0734242X1773537. <https://doi.org/10.1177/0734242X17735375>
- Amlinger, F., Peyr, S., & Cuhls, C. (2008). Green house gas emissions from composting and mechanical biological treatment. *Waste Management & Research*, 26(1), 47–60. <https://doi.org/10.1177/0734242X07088432>
- Andersen, J. K., Boldrin, A., Christensen, T. H., & Scheutz, C. (2010). Mass balances and life-cycle inventory for a garden waste windrow composting plant (Aarhus, Denmark). *Waste Management & Research*, 28(11), 1010–1020. <https://doi.org/10.1177/0734242X10360216>
- Angelo, A. C. M., Saraiva, A. B., Clímaco, J. C. N., Infante, C. E., & Valle, R. (2017). Life Cycle Assessment and Multi-criteria Decision Analysis: Selection of a strategy for domestic food waste management in Rio de Janeiro, 143, 744–756.
- Aquino, I. F. De, Castilho Jr., A. B. De, & Pires, T. S. D. L. (2009). A organização em rede dos catadores de materiais recicláveis na cadeia produtiva reversa de pós-consumo da região da grande Florianópolis: uma alternativa de agregação de valor. *Gestão & Produção*, 16(1), 15–24. <https://doi.org/10.1590/S0104-530X2009000100003>
- Bakas, I., Laurent, A., Clavreul, J., Saraiva, A. B., Niero, M., Gentil, E., & Hauschild, M. Z.

- (2018). LCA of Solid Waste Management Systems. In *Life Cycle Assessment* (pp. 887–926). https://doi.org/10.1007/978-3-319-56475-3_35
- Bassi, S. A., Christensen, T. H., & Damgaard, A. (2017a). *Environmental performance of household waste management in Europe - an example of 7 countries*. Technical University of Denmark. Lyngby, Denmark. <https://doi.org/10.1016/j.wasman.2017.07.042>
- Bassi, S. A., Christensen, T. H., & Damgaard, A. (2017b). Environmental performance of household waste management in Europe - an example of 7 countries. *Waste Management*, 111. <https://doi.org/10.1016/j.wasman.2017.07.042>
- Bernstad Saraiva, A., & Andersson, T. (2014). Food waste minimization from a life-cycle perspective. *Journal of Environmental Management*, 147(April), 219–226. <https://doi.org/10.1016/j.jenvman.2014.07.048>
- Bernstad Saraiva, A., Souza, R. G., & Valle, R. A. B. (2017). Comparative lifecycle assessment of alternatives for waste management in Rio de Janeiro – Investigating the influence of an attributional or consequential approach. *Waste Management*, 68, 701–710. <https://doi.org/10.1016/j.wasman.2017.07.002>
- Bisinella, V., Götze, R., Conradsen, K., Damgaard, A., Christensen, T. H., & Astrup, T. F. (2017). Importance of waste composition for Life Cycle Assessment of waste management solutions. *Journal of Cleaner Production*, 164, 1180–1191. <https://doi.org/10.1016/j.jclepro.2017.07.013>
- Boldrin, A., & Christensen, T. H. (2010). Seasonal generation and composition of garden waste in Aarhus (Denmark). *Waste Management*, 30(4), 551–557. <https://doi.org/10.1016/j.wasman.2009.11.031>
- Brasil. Lei 12.305, de 2 de agosto (2010). Brasília, DF, Brasil: nstitui a Política Nacional de Resíduos Sólidos; altera a Lei no 9.605, de 12 de fevereiro de 1998; e dá outras providências. Retrieved from http://www.planalto.gov.br/ccivil_03/_ato2007-2010/2010/lei/112305.htm
- Brouwer, M. T., Thoden van Velzen, E. U., Augustinus, A., Soethoudt, H., De Meester, S., & Ragaert, K. (2018). Predictive model for the Dutch post-consumer plastic packaging recycling system and implications for the circular economy. *Waste Management*, 71, 62–85. <https://doi.org/10.1016/j.wasman.2017.10.034>
- Campos, H. K. T. (2014). Recycling in Brazil: Challenges and prospects. *Resources, Conservation and Recycling*, 85, 130–138. <https://doi.org/10.1016/j.resconrec.2013.10.017>
- CEMPRE. (2010). *Lixo Municipal: Manual de Gerenciamento Integrado* (3rd ed.). CEMPRES.

- Christensen, T. (2011). *Solid waste technology and management*. Chichester West Sussex: Wiley.
- Christensen, T H, Gentil, E., Boldrin, A., Larsen, A. W., Weidema, B. P., & Hauschild, M. (2009). C balance, carbon dioxide emissions and global warming potentials in LCA-modelling of waste management systems. *Waste Management & Research*, 27(8), 707–715. <https://doi.org/10.1177/0734242x08096304>
- Christensen, Thomas H, Simion, F., Tonini, D., & Møller, J. (2009). Global warming factors modelled for 40 generic municipal waste management scenarios. *Waste Management & Research: The Journal of the International Solid Wastes and Public Cleansing Association, ISWA*, 27(9), 871–884. <https://doi.org/10.1177/0734242X09350333>
- Cimpan, C., Maul, A., Jansen, M., Pretz, T., & Wenzel, H. (2015). Central sorting and recovery of MSW recyclable materials: A review of technological state-of-the-art, cases, practice and implications for materials recycling. *Journal of Environmental Management*, 156, 181–199. <https://doi.org/10.1016/j.jenvman.2015.03.025>
- Cimpan, C., Maul, A., Wenzel, H., & Pretz, T. (2016). Techno-economic assessment of central sorting at material recovery facilities - The case of lightweight packaging waste. *Journal of Cleaner Production*, 112, 4387–4397. <https://doi.org/10.1016/j.jclepro.2015.09.011>
- Cimpan, C., Rothmann, M., Hamelin, L., & Wenzel, H. (2015). Towards increased recycling of household waste: Documenting cascading effects and material efficiency of commingled recyclables and biowaste collection. *Journal of Environmental Management*, 157, 69–83. <https://doi.org/10.1016/j.jenvman.2015.04.008>
- Cimpan, C., & Wenzel, H. (2013). Energy implications of mechanical and mechanical-biological treatment compared to direct waste-to-energy. *Waste Management*, 33(7), 1648–1658. <https://doi.org/10.1016/j.wasman.2013.03.026>
- Clavreul, J., Baumeister, H., Christensen, T. H., & Damgaard, A. (2014). An environmental assessment system for environmental technologies. *Environmental Modelling & Software*, 60, 18–30. <https://doi.org/10.1016/j.envsoft.2014.06.007>
- Clift, R., Doig, A., & Finnveden, G. (2000). The Application of Life Cycle Assessment to Integrated Solid Waste Management. *Trans IChemE*, 78(4), 279–287. <https://doi.org/10.1205/095758200530790>
- Coelho, L. M. G., & Lange, L. C. (2016). Applying life cycle assessment to support environmentally sustainable waste management strategies in Brazil. *Resources, Conservation and Recycling*, 13. <https://doi.org/10.1016/j.resconrec.2016.09.026>
- Colón, J., Cadena, E., Pognani, M., Maulini, C., Barrena, R., Sánchez, A., ... Artola, A. (2015).

- Environmental burdens of source-selected biowaste treatments: comparing scenarios to fulfil the European Union landfill directive. The case of Catalonia. *Journal of Integrative Environmental Sciences*, 12(3), 165–187. <https://doi.org/10.1080/1943815X.2015.1062030>
- Colvero, D. A., Pfeiffer, S. C., & Carvalho, E. H. de. (2016). Materiais recicláveis provindos dos resíduos urbanos: caso de estudo para o estado de Goiás, Brasil. In & M. J. R. In P. J. Ramísio, G. A. Lopes, L. M. C. Pinto, F. Leite (Ed.), *A Engenharia Sanitária nas Cidades do Futuro: livro de comunicações do 17º Encontro de Engenharia Sanitária e Ambiental/ENASB*. ISBN: 978-989-20-6908-8 (p. 888). Lisboa, Portugal. <https://doi.org/10.22181/17ENASB.2016>
- COMLURB. (2009). *Caracterização gravimétrica e microbiológica dos resíduos sólidos domiciliares – 2009*. Rio de Janeiro, RJ, Brasil.
- Cong, R. G., Caro, D., & Thomsen, M. (2017). Is it beneficial to use biogas in the Danish transport sector? – An environmental-economic analysis. *Journal of Cleaner Production*, 165, 1025–1035. <https://doi.org/10.1016/j.jclepro.2017.07.183>
- Conke, L. S. (2018). Barriers to waste recycling development: Evidence from Brazil. *Resources, Conservation and Recycling*, 134(March), 129–135. <https://doi.org/10.1016/j.resconrec.2018.03.007>
- Dahlbo, H., Poliakova, V., Mylläri, V., Sahimaa, O., & Anderson, R. (2018). Recycling potential of post-consumer plastic packaging waste in Finland. *Waste Management*, 71, 52–61. <https://doi.org/10.1016/j.wasman.2017.10.033>
- Dallmann, T., & Façanha, C. (2015). Brazil is not ready for diesel cars. Washington DC: International Council on Clean Transportation.
- Das Neves, M. G. F. P., & Tucci, C. E. M. (2011). Composição de resíduos de varrição e resíduos carreados pela rede de drenagem, em uma bacia hidrográfica urbana. *Engenharia Sanitária e Ambiental*, 16(4), 331–336. <https://doi.org/10.1590/S1413-41522011000400003>
- De Almeida, R. G. (2012). Estudo da Geração de resíduos sólidos domiciliares urbanos do município de Caçador SC, a partir da caracterização física e composição gravimétrica. *Ignis - Revista de Engenharias e Inovação Tecnológica*, 1(1 (jan./jun.)), 51–70. Retrieved from <http://www.uniarp.edu.br/periodicos/index.php/ignis/article/view/30%5Cnpapers3://publication/uuid/C0825340-1C06-41BD-AAF8-2A1BCB773E7F>
- de Beer, J., Cihlar, J., Hensing, I., & Zabeti, M. (2017). *Recent Development on the Uses of*

Alternative Fuels in Cement Manufacturing Process.

- de Oliveira, E. G. (2012). *Qualificação de Resíduos Sólidos gerados em uma feira livre na cidade de Campina Grande - PB*. Universidade Estadual da Paraíba.
- DEFRA. (2011). *Emissions from Waste Management Facilities, WR 0608*. London, UK: Department for Environment, Food and Rural Affairs (Defra).
- Delgado, O., & Muncrief, R. (2015). *Assessment of Heavy-Duty Natural Gas Vehicle Emissions: Implications and Policy Recommendations*. Washington DC.
- Deus, R. M., Battistelle, R. A. G., & Silva, G. H. R. (2017). Current and future environmental impact of household solid waste management scenarios for a region of Brazil: carbon dioxide and energy analysis. *Journal of Cleaner Production*, 155, 218–228. <https://doi.org/10.1016/j.jclepro.2016.05.158>
- Dicks, G., & Breedon, F. (1988). *World Outlook. Economic Outlook* (Vol. 12). <https://doi.org/10.1111/j.1468-0319.1988.tb00400.x>
- DTU. (2016). *EASETECH Impact categories and impact methods*. Kgs. Lyngby, Denmark. Retrieved from Personal Communication with Dr. Anders Damgaard, DTU.
- EC-JRC. (2011). *General guide for Life Cycle Assessment - Detailed guidance. International Reference Life Cycle Data System (ILCD) Handbook* (First). Luxembourg: Publications Office of the European Union. <https://doi.org/10.2788/38479>
- European Commission. (2006). *Best Available Techniques for the Waste Treatment Industries – reference document*. Seville, Spain: Integrated Pollution Prevention and Control Bureau, Joint Research Centre.
- Faria, M. R. A. (2005). Caracterização do resíduo sólido urbano da cidade de Leopoldina-MG: proposta de implantação de um centro de triagem. *Revista APS*, 8(2 (jul./dez.)), 96–108.
- Feil, A., Pretz, T., Jansen, M., & Thoden Van Velzen, E. U. (2017). Separate collection of plastic waste, better than technical sorting from municipal solid waste? *Waste Management and Research*, 35(2), 172–180. <https://doi.org/10.1177/0734242X16654978>
- Ferreira, J. A., & Anjos, L. A. (2001). Aspectos de saúde coletiva e ocupacional associados à gestão dos resíduos sólidos municipais Public and occupational health issues related to municipal solid waste management. *Cad. Saúde Pública*, 17(3), 689–696. <https://doi.org/10.1590/S0102-311X2001000300023>
- Fricke, K., Santen, H., & Wallmann, R. (2005). Comparison of selected aerobic and anaerobic procedures for MSW treatment. *Waste Management*, 25(8), 799–810. <https://doi.org/10.1016/j.wasman.2004.12.018>
- Genon, G., & Brizio, E. (2008). Perspectives and limits for cement kilns as a destination for

- RDF. *Waste Management*, 28(11), 2375–2385.
<https://doi.org/10.1016/j.wasman.2007.10.022>
- Gentil, E., Clavreul, J., & Christensen, T. H. (2009). Global warming factor of municipal solid waste management in Europe. *Waste Management & Research: The Journal of the International Solid Wastes and Public Cleansing Association, ISWA*, 27(9), 850–860.
<https://doi.org/10.1177/0734242X09350659>
- Goulart Coelho, L. M., & Lange, L. C. (2018). Applying life cycle assessment to support environmentally sustainable waste management strategies in Brazil. *Resources, Conservation and Recycling*, 128, 438–450.
<https://doi.org/10.1016/j.resconrec.2016.09.026>
- Grosso, M., Dellavedova, S., Rigamonti, L., & Scotti, S. (2016). Case study of an MBT plant producing SRF for cement kiln co-combustion, coupled with a bioreactor landfill for process residues. *Waste Management*, 47, 267–275.
<https://doi.org/10.1016/j.wasman.2015.10.017>
- Guerrero, L. A., Maas, G., & Hogland, W. (2013). Solid waste management challenges for cities in developing countries. *Waste Management*, 33(1), 220–232.
<https://doi.org/10.1016/j.wasman.2012.09.008>
- Hakawati, R., Smyth, B. M., McCullough, G., De Rosa, F., & Rooney, D. (2017). What is the most energy efficient route for biogas utilization: Heat, electricity or transport? *Applied Energy*, 206, 1076–1087. <https://doi.org/10.1016/j.apenergy.2017.08.068>
- Heck, K., Marco, É. G. De, Hahn, A. B. B., Kluge, M., Spilki, F. R., & Sand, S. T. Van Der. (2013). Temperatura de degradação de resíduos em processo de compostagem e qualidade microbiológica do composto final. *Revista Brasileira de Engenharia Agrícola e Ambiental*, 17(1), 54–59. <https://doi.org/10.1590/S1415-43662013000100008>
- Hoornweg, D., & Bhada-Tata, P. (2012). A Global Review of Solid Waste Management. *World Bank Urban Development Series Knowledge Papers*, 1–116.
<https://doi.org/10.1111/febs.13058>
- Ibáñez-Forés, V., Bovea, M. D., Coutinho-Nóbrega, C., de Medeiros-García, H. R., & Barreto-Lins, R. (2017). Temporal evolution of the environmental performance of implementing selective collection in municipal waste management systems in developing countries: A Brazilian case study. *Waste Management*, 72, 65–77.
<https://doi.org/10.1016/j.wasman.2017.10.027>
- Ibáñez-Forés, V., Coutinho-Nóbrega, C., Bovea, M. D., de Medeiros, H. R., & Barreto, R. (2017). Influence of implementing selective collection in municipal waste management

- systems in developing countries: a Brazilian case study. *Sustainability Science*, (in press).
<https://doi.org/10.1016/j.wasman.2017.10.027>
- IBGE. (2010). *Atlas Nacional do Brasil*. (IBGE, Ed.).
- IBGE. (2019). Projeção da população do Brasil e das Unidades da Federação. Retrieved March 1, 2019, from <https://www.ibge.gov.br/apps/populacao/projecao/>
- IEA. (2017). *World Energy Outlook 2017*. International Energy Agency. Paris, France.
[https://doi.org/10.1016/0301-4215\(73\)90024-4](https://doi.org/10.1016/0301-4215(73)90024-4)
- IFC. (2017). *Increasing the Use of Alternative Fuels at Cement Plants : International Best Practice*. Washington, DC.
- Koci, V., & Trecakova, T. (2011). Mixed municipal waste management in the Czech Republic from the point of view of the LCA method. *International Journal of Life Cycle Assessment*, 16(2), 113–124. <https://doi.org/10.1007/s11367-011-0251-4>
- Kulczycka, J., Lelek, L., Lewandowska, A., & Zarebska, J. (2015). Life Cycle Assessment of Municipal Solid Waste Management – Comparison of Results Using Different LCA Models. *Polish Journal of Environmental Studies*, 24(1), 125–140.
<https://doi.org/10.15244/pjoes/26960>
- Lagerkvist, A., Ecke, H., & Christensen, T. H. (2011). Waste characterization: Approaches and methods. *Solid Waste Technology and Management*.
- Leme, M. M. V., Rocha, M. H., Lora, E. E. S., Venturini, O. J., Lopes, B. M., & Ferreira, C. H. (2014). Techno-economic analysis and environmental impact assessment of energy recovery from Municipal Solid Waste (MSW) in Brazil. *Resources, Conservation and Recycling*, 87, 8–20. <https://doi.org/10.1016/j.resconrec.2014.03.003>
- Leme, M. M. V., Rocha, M. H., Silva, E. E. L., Lopes, B. M., & Ferreira, C. H. (2012). Environmental assessment of energy recovery technologies for the treatment and disposal of municipal solid waste using Life Cycle Assessment (LCA): A case study of Brazil. In *PROCEEDINGS OF ECOS 2012 - THE 25TH INTERNATIONAL CONFERENCE ON EFFICIENCY, COST, OPTIMIZATION, SIMULATION AND ENVIRONMENTAL IMPACT OF ENERGY SYSTEMS* (pp. 1–9). Perugia, Italy.
- Liamsanguan, C., & Gheewala, S. H. (2008). The holistic impact of integrated solid waste management on greenhouse gas emissions in Phuket. *Journal of Cleaner Production*, 16(17), 1865–1871. <https://doi.org/10.1016/j.jclepro.2007.12.008>
- Liikanen, M., Havukainen, J., Viana, E., & Horttanainen, M. (2018). Steps towards more environmentally sustainable municipal solid waste management – A life cycle assessment study of São Paulo, Brazil. *Journal of Cleaner Production*, 196, 150–162.

- <https://doi.org/10.1016/j.jclepro.2018.06.005>
- Lima, J. D. De, Juca, J. F. T., Reichert, G. A., & Firmo, A. L. B. (2014). Uso de modelos de apoio a decisao para analise de alternativas tecnologicas de tratamento de residuos solidos urbanos na Regiao Sul do Brasil. *Engenharia Sanitaria e Ambiental*, 19(1), 33–42. <https://doi.org/10.1590/S1413-41522014000100004>
- Lima, P. D. M., Colvero, D. A., Gomes, A. P., Wenzel, H., Schalch, V., & Cimpan, C. (2018). Environmental assessment of existing and alternative options for management of municipal solid waste in Brazil. *Waste Management*, 78, 857–870. <https://doi.org/10.1016/j.wasman.2018.07.007>
- Macêdo, J. dos S. (2011). *O trabalho dos catadores de lixo na cidade de Riachão - PB*. Universidade Estadual da Paraíba.
- Maiello, A., Lucia, A., De, N., Britto, P., & Freitas Valle, T. (2018). Implementação da Política Nacional de Resíduos Sólidos Implementación de la Política Nacional Brasileña de Gestión de Residuos, 52(1), 24–51. <https://doi.org/10.1590/0034-7612155117>
- Manfredi, S., & Christensen, T. H. (2009). Environmental assessment of solid waste landfilling technologies by means of LCA-modeling. *Waste Management*, 29(1), 32–43. <https://doi.org/10.1016/j.wasman.2008.02.021>
- Manzi, D. H. dos S. (2017). *Setorização Socioeconômica como embasamento ao gerenciamento e manejo de resíduos sólidos domiciliares*. Universidade Federal de Mato Grosso do Sul.
- McDougall, F., White, P., Franke, M., & Hindle, P. (2001). *Integrated solid waste management: a life cycle inventory* (2nd ed.). Malden: Blackwell Science. Retrieved from <http://onlinelibrary.wiley.com/doi/10.1002/cbdv.200490137/abstract%5Cnhttp://books.google.com/books?hl=en&lr=&id=Mcq-hYQSOWAC&oi=fnd&pg=PR5&dq=Integrated+Solid+Waste+Management:+a+Life+Cycle+Inventory&ots=ZyF9jUTOsI&sig=yNlzlFI7aLPYshOemkMKRhEHIJs>
- Mendes, M. R., Aramaki, T., & Hanaki, K. (2004). Comparison of the environmental impact of incineration and landfilling in São Paulo City as determined by LCA. *Resources, Conservation and Recycling*, 41(1), 47–63. <https://doi.org/10.1016/j.resconrec.2003.08.003>
- Mersoni, C., & Reichert, G. A. (2017). Comparação de cenários de tratamento de resíduos sólidos urbanos por meio da técnica da Avaliação do Ciclo de Vida: o caso do município de Garibaldi, RS. *Engenharia Sanitaria e Ambiental*, 22(5), 863–875. <https://doi.org/10.1590/s1413-41522017150351>

- MMA, M. do M. A. (2012). *Plano Nacional de Resíduos Sólidos - PLANARES*. Brasília, DF. Retrieved from <http://www.sinir.gov.br/web/guest/plano-nacional-de-residuos-solidos>
- MME, M. de M. e E. (2017). *Resenha Energética Brasileira - Exercício de 2016*. Brasília - DF. Retrieved from www.mme.gov.br/documents/10584/3580498/02+-+Resenha+Energética+Brasileira+2017+-+ano+ref.+2016+%28PDF%29/13d8d958-de50-4691-96e3-3ccf53f8e1e4?version=1.0
- Møller, J., Jensen, M. B., Kromann, M., Neidel, T. L., & Jakobsen, B. (2013). *Miljø- og samfundsøkonomisk vurdering af muligheder for øget genanvendelse af papir, pap, plast, metal og organisk affald fra dagrenovation. Miljøprojekt nr. 1458*. <https://doi.org/978-87-92903-80-8>
- Moura, A. A. de, Lima, W. S. de, & Archanjo, C. do R. (2012). Análise da composição gravimétrica de resíduos sólidos urbanos: estudo de caso - município de Itaúna - MG. *SynThesis Revista Digital FAPAM*, (3 (abr.)), 4–16.
- Münnich, K., Mahler, C. F., & Fricke, K. (2006). Pilot project of mechanical-biological treatment of waste in Brazil. *Waste Management*, 26(2), 150–157. <https://doi.org/10.1016/j.wasman.2005.07.022>
- Naroznova, I., Møller, J., Larsen, B., & Scheutz, C. (2016a). Evaluation of a new pulping technology for pre-treating source-separated organic household waste prior to anaerobic digestion. *Waste Management*, 50, 65–74. <https://doi.org/10.1016/j.wasman.2016.01.042>
- Naroznova, I., Møller, J., Larsen, B., & Scheutz, C. (2016b). Evaluation of a new pulping technology for pre-treating source-separated organic household waste prior to anaerobic digestion. *Waste Management*, 50, 65–74. <https://doi.org/10.1016/j.wasman.2016.01.042>
- Naroznova, I., Møller, J., & Scheutz, C. (2016). Characterisation of the biochemical methane potential (BMP) of individual material fractions in Danish source-separated organic household waste. *Waste Management*, 50, 39–48. <https://doi.org/10.1016/j.wasman.2016.02.008>
- Neto, J. P. F., Lima, J. D. de, Queiroz, M. A. de, & Nóbrega, C. C. (1999). Determinação da composição gravimétrica dos resíduos sólidos domiciliares do município de João Pessoa - PB. In *20º Congresso Brasileiro de Engenharia Sanitária e Ambiental* (pp. 3650–3659). Rio de Janeiro, RJ, Brasil.
- Olesen, O. U., & Damgaard, A. (2014). *Landfilling in EASETECH - Data collection and modelling of the landfill modules in EASETECH*.
- Pasqualetto, A., Andrade, H. da F., Prado, M. L. do, & Pina, G. P. R. de. (2004). Caracterização física dos resíduos sólidos domésticos do município de Caldas Novas – GO. *Biblioteca*

- Virtual de Desarrollo Sostenible y Salud Ambiental*, 1–8.
- Pessin, N., Conto, S. M. de, Telh, M., Cadore, J., Rovatti, D., & Boff, R. E. (2006). Composição gravimétrica de resíduos sólidos urbanos: estudo de caso – município de Canela – RS. *Congresso Interamericano de Ingeniería Sanitaria y Ambiental*, (1), 112–120.
- Pin, B. V. R., Barros, R. M., Silva Lora, E. E., & dos Santos, I. F. S. (2018). Waste management studies in a Brazilian microregion: GHG emissions balance and LFG energy project economic feasibility analysis. *Energy Strategy Reviews*, 19, 31–43. <https://doi.org/10.1016/j.esr.2017.11.002>
- PMCG, & DMTR. (2017a). *Plano de Coleta Seletiva - Estudo de caracterização física dos resíduos sólidos*. Campo Grande, MS, Brasil.
- PMCG, & DMTR. (2017b). *Plano de Coleta Seletiva de Campo Grande/MS. Estudo de caracterização física dos resíduos sólidos - versão 01*. Campo Grande, MS, Brasil.
- PMCG, & DMTR. (2017c). *Plano de Coleta Seletiva de Campo Grande/MS - Tomo I-IV [Plan for Selective Collection in Campo Grande - Volume I-IV (In Portuguese)]*. Campo Grande, MS, Brasil. Retrieved from <http://pscsgdmtr.wixsite.com/coletaseletiva/downloads>
- Rahman, A., Rasul, M. G., Khan, M. M. K., & Sharma, S. (2015). Recent development on the uses of alternative fuels in cement manufacturing process. *Fuel*. <https://doi.org/10.1016/j.fuel.2014.12.029>
- Reichert, G. A., & Mendes, C. A. B. (2014). Avaliação do ciclo de vida e apoio à decisão em gerenciamento integrado e sustentável de resíduos sólidos urbanos. *Engenharia Sanitaria e Ambiental*, 19(3), 301–313. <https://doi.org/10.1590/S1413-41522014019000001145>
- Rezende, J. H., Carboni, M., Murgel, M. A. de T., Capps, A. L. de A. P., Teixeira, H. L., Simões, G. T. C., ... Oliveira, C. de A. (2013). Composição gravimétrica e peso específico dos resíduos sólidos urbanos em Jaú (SP). *Engenharia Sanitaria e Ambiental*, 18(1), 1–8. <https://doi.org/10.1590/S1413-41522013000100001>
- Riber, C., Petersen, C., & Christensen, T. H. (2009). Chemical composition of material fractions in Danish household waste. *Waste Management*, 29(4), 1251–1257. <https://doi.org/10.1016/j.wasman.2008.09.013>
- Rigamonti, L., Grosso, M., & Biganzoli, L. (2012). Environmental Assessment of Refuse-Derived Fuel Co-Combustion in a Coal-Fired Power Plant. *Journal of Industrial Ecology*, 16(5), 748–760. <https://doi.org/10.1111/j.1530-9290.2011.00428.x>
- Rodić, L., & Wilson, D. C. (2017). Resolving governance issues to achieve priority sustainable development goals related to solid waste management in developing countries. *Sustainability (Switzerland)*, 9(3), 1–18. <https://doi.org/10.3390/su9030404>

- Rosa, B. P., Paula, B. C. D. L., Soares, E., Coleone, A., Campos, F., & Cep, P. (2017). Impactos causados em cursos d' água por aterros controlados desativados no Município de São Paulo, Sudeste do Brasil. *Revista Brasileira de Gestão Ambiental e Sustentabilidade*, 4(2359–1412), 63–76.
- Sala, S., Crenna, E., Secchi, M., & Pant, R. (2017). *Global normalisation factors for the Environmental Footprint and Life Cycle Assessment*. <https://doi.org/10.2760/88930>
- Schalch, V., Leite, W. C. de A., Fernandes Junior, J. L., & De Castro, M. C. A. A. (2002). *Gestão e Gerenciamento De Resíduos*. São Carlos.
- Schmidt, J. H., Merciai, S., Thrane, M., & Dalgaard, R. (2011). Inventory of country specific electricity in LCA - Consequential and attributional scenarios. Methodology report v2. *Inventory Report V2*, 26. Retrieved from <http://lca-net.com/p/212>
- Seelig, M. F., & Schneider, P. S. (2012). Estimating the energy content of municipal solid waste from its physical composition : the heat of combustion of Porto Alegre's household solid waste. In *14th Brazilian Congress of Thermal Sciences and Engineering* (pp. 14–18). Rio de Janeiro, RJ, Brasil. Retrieved from <http://abcm.org.br/anais/encit/2012/links/pdf/ENCIT2012-394.pdf>
- SEMASA, S. M. de S. A. de S. A. (2008). *Caracterização gravimétrica dos resíduos sólidos urbanos domiciliares do município de Santo André*. Santo André, SP, Brasil.
- SEMMA, S. M. de M. A. de A. (2013). *Definição da composição gravimétrica por meio do método de quarteamento para a caracterização quantitativa e qualitativa dos resíduos sólidos domiciliares do município de Anápolis - GO*. Anápolis, GO, Brasil.
- SNIS. (2016). Diagnóstico do Manejo de Resíduos Sólidos Urbanos - 2014. *Snis*, 53, 1689–1699. <https://doi.org/10.1017/CBO9781107415324.004>
- SNIS, S. N. de I. sobre S. (2017). Diagnóstico do Manejo de Resíduos Sólidos Urbanos - 2015, 173. Retrieved from <http://www.snis.gov.br/diagnostico-residuos-solidos/diagnostico-rs-2015>
- SNSA - Secretaria Nacional de Saneamento Ambiental. (2016). *Diagnóstico do manejo de resíduos sólidos urbanos - 2014*. Brasília, DF, Brasil. <https://doi.org/10.1017/CBO9781107415324.004>
- Soares, E. L. de S. F. (2011). *Estudo Da Caracterização Gravimétrica E Poder Calorífico Dos Resíduos Sólidos Urbanos*. Universidade Federal do Rio de Janeiro.
- Soares, F. R. (2017). Using Life Cycle Assessment to Compare Environmental Impacts of Different Waste to Energy Options for Sao Paulo's Municipal Solid Waste. *The Journal of Solid Waste Technology and Management*, 43(1), 36–46.

<https://doi.org/10.5276/JSWTM.2017.36>

- Soares, F. R., Miyamaru, E. S., & Martins, G. (2017). Desempenho ambiental da destinação e do tratamento de resíduos sólidos urbanos com reaproveitamento energético por meio da avaliação do ciclo de vida na Central de Tratamento de Resíduos - Caieiras. *Engenharia Sanitaria e Ambiental*, 22(5), 993–1003. <https://doi.org/10.1590/s1413-41522017155522>
- Song, Q., Wang, Z., & Li, J. (2013). Environmental performance of municipal solid waste strategies based on LCA method: A case study of Macau. *Journal of Cleaner Production*, 57(April), 92–100. <https://doi.org/10.1016/j.jclepro.2013.04.042>
- Tabalipa, N. L., & Fiori, A. P. (2006). Caracterização e classificação dos resíduos sólidos urbanos do município de Pato Branco, PR. *Revista Brasileira de Ciências Ambientais*, (4), 23–33.
- Thomanetz, E. (2012). Solid recovered fuels in the cement industry with special respect to hazardous waste. *Waste Management & Research*, 30(4), 404–412. <https://doi.org/10.1177/0734242X12440480>
- Trulli, E., Ferronato, N., Torretta, V., Piscitelli, M., Masi, S., & Mancini, I. (2018). Sustainable mechanical biological treatment of solid waste in urbanized areas with low recycling rates. *Waste Management*, 71, 556–564. <https://doi.org/10.1016/j.wasman.2017.10.018>
- Vaz, L. M. S., Costa, B. N., Gusmão, O. da S., & Azevedo, L. S. (2003). Diagnóstico dos resíduos sólidos produzidos em uma feira livre: o caso da feira do tomba. *Sitientibus*, (28), 145–159. Retrieved from http://www2.uefs.br:8081/sitientibus/pdf/28/diagnostico_dos_residuos_solidos.pdf
- Velis, C. A., Longhurst, P. J., Drew, G. H., Smith, R., & Pollard, S. J. T. (2009). Biodrying for mechanical-biological treatment of wastes: A review of process science and engineering. *Bioresource Technology*, 100, 2747–2761. <https://doi.org/10.1016/j.biortech.2008.12.026>
- Veloso, S. (2014). *BRICS and the challenges of fighting inequality*. Rio de Janeiro.
- Vergara, S. E., Damgaard, A., & Gomez, D. (2016). The Efficiency of Informality: Quantifying Greenhouse Gas Reductions from Informal Recycling in Bogotá, Colombia. *Journal of Industrial Ecology*, 20(1), 107–119. <https://doi.org/10.1111/jiec.12257>
- Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. *International Journal of Life Cycle Assessment*, 21(9), 1218–1230. <https://doi.org/10.1007/s11367-016-1087-8>
- Williams, A. S. (2009). Life Cycle Analysis: A Step by Step Approach, (December), 23. https://doi.org/http://www.istc.illinois.edu/info/library_docs/tr/tr40.pdf

Wilson, D. C., Velis, C. A., & Rodic, L. (2013). Integrated sustainable waste management in developing countries. *Proceedings of the ICE - Waste and Resource Management*.

APPENDICES

APPENDIX A

Waste Generation MSW – Brazil

In order to establish an average gravimetric composition for the Brazilian MSW, we considered 15 Municipalities distributed in 10 States throughout Brazil. The studies we used for the calculations were from different sizes Municipalities (Table A-1), such as Canela (state of Rio Grande do Sul) that in 2010 had 39,229 inhabitants and Rio de Janeiro (state of Rio de Janeiro) that in the same year presented a population of 6,320,446 inhabitants (IBGE, 2010). The gravimetric composition was established by the population size and each Municipalities' gravimetric composition. First, we added the population of the 15 municipalities in 2010 (last official data from IBGE) and this value with each gravimetric composition was used to calculate the percentage of gravimetric contribution in the Brazilian average. In other words, as done by Colvero et al. (2016) we performed a weighted average for the waste composition in Brazil.

Table A-1 – Brazilian municipalities with its states and population that were used for the Brazilian average gravimetric composition.

Municipality	State	Population in 2010	Citation
Cáceres	Mato Grosso	87,942 inhabitants	(Alcantara, 2010)
Rio de Janeiro	Rio de Janeiro	6,320,446 inhabitants	(COMLURB, 2009)
Caçador	Santa Catarina	70,762 inhabitants	(De Almeida, 2012)
Leopoldina	Minas Gerais	51,130 inhabitants	(Faria, 2005)
Itaúna	Minas Gerais	85,463 inhabitants	(Moura, Lima, & Archanjo, 2012)
João Pessoa	Paraíba	723,515 inhabitants	(Neto, Lima, Queiroz, & Nóbrega, 1999)
Caldas Novas	Goiás	70,473 inhabitants	(Pasqualetto, Andrade, Prado, & Pina, 2004)
Canela	Rio Grande do Sul	39,229 inhabitants	(Pessin et al., 2006)
Campo Grande	Mato Grosso do Sul	786,797 inhabitants	(PMCG & DMTR, 2017b)
Jaú	São Paulo	131,040 inhabitants	(Rezende et al., 2013)
Porto Alegre	Rio Grando do Sul	1,409,351 inhabitants	(Seelig & Schneider, 2012)
Santo André	São Paulo	676,407 inhabitants	(SEMASA, 2008)
Anápolis	Goiás	334,613 inhabitants	(SEMMA, 2013)
Nova Iguaçu	Rio de Janeiro	796,257 inhabitants	(E. L. de S. F. Soares, 2011)
Pato Branco	Paraná	72,370 inhabitants	(Tabalipa & Fiori, 2006)

The results were then subtracted by the informal sector contribution to the waste collection. Therefore, 3.6% was diverted from the original numbers, based on the pickers' preferences as described by Macêdo (2011): paper – 44%; cardboard – 4%; metals – 18%; glass – 7%; and plastics – 27%. After these were applied the average MSW found for Brazil was

composed of 54.9% of organic matter, 34.1% of recyclables and 11% of other (Table A-2). Furthermore, it is important to stress that the 15 studies used for the gravimetric composition do not estimate the different fractions of food waste, i.e. vegetable waste and animal waste. Therefore, we considered the research by Bernstad Saraiva & Andersson (2014) in which the organics are composed of 12% vegetable waste and 88% animal waste.

Table A-2 – Average gravimetric composition of the Brazilian Municipalities before the informal sector.

Waste type (EASETECH denominations)	Brazil
Paper	6.28
Paper (Office Paper)	5.26
Kitchen paper, among others (other clean paper)	0.34
Magazines	0.07
Newsprint	0.34
Clean Cardboard	6.79
Multilayer Packaging (Juice cartons)	0.27
Metals	1.14
Ferrous metal (food cans)	1.06
Aluminium (beverage cans)	0.08
Glass	2.27
Colorless glass (clear glass)	2.14
Colored glass (brown glass)	0.13
Plastics	17.53
Rigid Plastic (hard plastic)	4.83
PET (plastic bottles)	0.63
2D Plastic (soft plastic)	9.49
Styrofoam (non-recyclable plastic)	0.84
Other plastic (Plastic Products)	1.75
Organic	54.85
Vegetable Food	48.27
Animal Food	6.59
Rejects	10.99
Sanitary (diapers, sanitary towels, tampons)	1.51
Rubber	0.27
Leather (shoes, leather)	0.23
Foam (Other combustibles)	0.10
Textiles	2.48
Wood (wood residues)	0.39
Other (other non-combustibles)	6.00
Hazardous	0.15
TOTAL	100.0%

Source: Adapted from Alcantara, 2010; Bernstad et al., 2014; COMLURB - Companhia Municipal de Limpeza Urbana, 2009; De Almeida, 2012; Faria, 2005; Moura, Lima, & Archanjo, 2012; Neto, Lima, Queiroz, & Nóbrega, 1999; Pasqualetto, Andrade, Prado, & Pina, 2004; Pessin et al., 2006; Prefeitura Municipal de Campo Grande, 2017; Rezende et al., 2013; Seelig & Schneider, 2012; SEMASA - Serviço Municipal de Saneamento Ambiental de Santo André, 2008; SEMMA - Secretaria Municipal de Meio Ambiente de Anápolis, 2013; Soares, 2011; Tabalipa & Fiori, 2006.

APPENDIX B

Detailed data on gravimetric compositions

Methodology from PMCG and DMTR (2017b): For regular mixed waste collection, 22 samples were collected from selected areas within the four designated sectors. The samples were full trucks returning from collection, containing around 9 tonnes of waste each. The total waste was used to determine bulk densities, followed by mixing and separation of 1 tonne reduced samples for the gravimetric composition analysis. The reduced samples were mixed and quartered two times resulting in a mass of around 200 kg that was characterized by hand picking analysis into 17 material fractions. Some outliers for different material fractions were discarded from the final weighted average composition determined for each sector.

For separate collection, a total of 35 samples (33 for door-to-door and 2 for ecopoints) were collected from three sectors (the “until 2.5” sector is not covered by separate collection). In this case, each truckload consisted of around 1.8 tonnes, and the final samples for hand picking analysis weighted around 50 kg.

The gravimetric composition from regular and selective collection, as for commercial and institutional waste and Ecopoints were obtained through a weighted average with the values presented in Table B-1 and Table B-, taken from the PCS.

Table B-1 – Gravimetric composition for each sector of the regular waste collection in Campo Grande.

	”until 2.5”	”2.51 to 5”	”5.01 to 7.5”	”7.51 to 10”	CAMPO GRANDE
Population	87,787	440,335	194,735	51,345	774,202
Cardboard	6.18%	11.52%	6.89%	4.63%	9.3%
White Paper	0.60%	0.84%	2.17%	5.03%	1.42%
Colored Paper	0.61%	0.43%	2.00%	1.02%	0.88%
Multilayer Packaging	1.00%	1.09%	0.93%	0.54%	1.0%
Paper total	2.21%	2.36%	5.10%	6.59%	3.30%
Ferrous Metal	1.24%	0.45%	0.84%	0.18%	0.62%
Aluminium	0.38%	0.18%	0.52%	0.57%	0.31%
Metals	1.62%	0.63%	1.36%	0.75%	0.93%
Colorless Glass	0.77%	0.65%	0.28%	0.70%	0.57%
Colored Glass	0.38%	2.18%	2.28%	2.24%	2.01%
Glass	1.15%	2.83%	2.56%	2.94%	2.58%
Rigid Plastic	1.96%	1.72%	1.50%	1.58%	1.68%
PET	1.26%	1.20%	1.26%	1.33%	1.23%
2D Plastic (film)	16.06%	16.49%	18.65%	11.44%	16.65%
Styrofoam	0.23%	0.29%	0.57%	0.96%	0.40%

	"until 2.5"	"2.51 to 5"	"5.01 to 7.5"	"7.51 to 10"	CAMPO GRANDE
Other Plastics	0.77%	0.89%	1.04%	0.91%	0.92%
Plastics	20.28%	20.59%	23.02%	16.22%	20.88%
Organic	48.34%	45.71%	42.94%	61.25%	46.34%
Sanitary	16.16%	10.53%	13.54%	6.29%	11.64%
Other	3.83%	5.77%	4.58%	1.32%	4.96%
Hazardous	0.23%	0.07%	0.00%	0.00%	0.07%
TOTAL	100.00%	100.00%	100.00%	100.00%	100.00%

Table B-2 –Gravimetric composition for each sector of the selective collection in Campo Grande (population covered by separate collection schemes)

	"2.51 to 5"	"5.01 to 7.5"	"7.51 to 10"	CAMPO GRANDE
Population	113,043	124,049	51,003	288,095
Cardboard	17.94%	18.00%	23.33%	18.9%
White Paper	3.18%	3.48%	2.91%	3.26%
Colored Paper	8.06%	5.58%	4.61%	6.38%
Multilayer Packaging	3.99%	3.71%	2.96%	3.69%
Paper total	15.23%	12.77%	10.48	13.33%
Ferrous Metal	2.75%	2.93%	1.91%	2.68%
Aluminium	1.60%	1.85%	1.78%	1.74%
Metals	4.35%	4.78%	3.69%	4.42%
Colorless Glass	2.36%	1.94%	3.98%	2.47%
Colored Glass	15.11%	11.48%	15.85%	13.68%
Glass	17.47%	13.42%	19.83%	16.15%
Rigid Plastic	6.99%	7.01%	4.48%	6.55%
PET	5.56%	5.60%	6.43%	5.73%
2D Plastic (film)	6.06%	8.47%	7.25%	7.3%
Styrofoam	0.48%	0.48%	0.60%	0.50%
Other Plastics	4.00%	3.87%	1.79%	3.55%
Plastics	23.09%	25.43%	20.55%	23.63%
Organic	0.85%	0.38%	1.96%	0.85%
Sanitary	1.27%	0.55%	3.93%	1.43%
Other	19.82%	24.67%	16.32%	21.29%
TOTAL	100.00%	100.00%	100.00%	100.00%