BERNA CAPAR

Life Cycle Assessment of Municipal Solid Waste Management in Megacities – The Example "Istanbul Metropolitan City of Türkiye"

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Hauptberichter: Univ.-Prof. Dr.-Ing. Martin Kranert
Mitberichter: Univ.-Prof. Dr.-Ing. Bülent Topkaya

Forschungs- und Entwicklungsinstitut für Industrie- und Siedlungswasserwirtschaft sowie Abfallwirtschaft e.V. (FEI)

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Life Cycle Assessment of Municipal Solid Waste Management in Megacities

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zur Erlangung der Würde einer Doktor-Ingenieurin (Dr.-Ing.)
genehmigte Abhandlung

Vorgelegt von

M.Sc. Berna Capar

aus Elazig, Türkei

Hauptberichter: Prof. Dr.-Ing. Martin Kranert
Mitberichter: Prof. Dr.-Ing. Bülent Topkaya

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FOREWORD

The number of megacities and their populations will continue to increase significantly worldwide in the coming decades. The high specific volumes of waste and the complex and, in many cases, inadequate disposal structures pose a major challenge. Worldwide, around 11% of municipal solid waste is currently generated in megacities, and the trend is rising. Waste management measures are of central importance here, especially with regard to resource and climate protection. This is particularly the case as especially in countries with emerging economies inadequate waste treatment, which mainly takes the form of landfilling, causes considerable greenhouse gas emissions due to the methane generated and groundwater pollution. The objectives of the circular economy are also not being achieved.

Future waste management systems must be evaluated especially from an ecological point of view to realize the United Nations Sustainable Development Goals. In addition to the life cycle assessment (LCA) criteria, the avoided emissions of fossil greenhouse gases through recycling and energy recovery from waste must also be considered at regional level.

Dr.-Ing. Berna Capar takes up this highly topical issues in her dissertation. The author developed an evaluation system for megacities with complex waste management structures under the above-mentioned aspects and its application. She is using the example of the Istanbul Metropolitan Municipality (Türkiye) with a population of 16 million inhabitants that continues to grow. 6,6 million Mg of municipal solid waste are generated annually, most of it is disposed of in landfills. Various scenarios have been developed including the existing waste management system in Istanbul (2020), the targets of Istanbul Metropolitan Municipality for the year 2023 and the EU targets for the year 2030.

With her dissertation, Dr.-Ing. Berna Capar has made an important scientific contribution to the development and evaluation of waste management systems at regional level, taking into account collection and recycling rates, thus filling open gaps in knowledge. For Türkiye she has shown for the first time how greenhouse gas emissions can be reduced through waste management measures, taking into account the national energy mix, using the example of Istanbul Metropolitan Municipality.

The quantitative results show that especially in megacities a move away from landfilling is necessary with regard to resource and climate protection as well to environmental protection based on seven impact categories in life cycle assessment. Separate collection and recycling of biowaste and dry recycling materials coupled with thermal treatment with energy recovery of residual waste is the most environmentally friendly solution. This significantly reduces fossil emissions both directly by generating energy and indirectly by recycling biogenic and non-biogenic or mineral product and material flows.

The scientific findings developed by Dr.-Ing. Berna Capar for the greater Istanbul Metropolitan Municipality area are also transferable to other megacities, especially in countries with emerging economies, and are important and useful not only for science but also for practice.

I wish this dissertation a wide recognition and dissemination among all experts in the field of solid waste management.

Stuttgart, July 2024 Prof. Dr.-Ing. Martin Kranert

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SYMBOLS AND ABBREVIATIONS

Symbols

Btu: British Thermal Units

eq: Equivalent

g: Gram

kg: Kilogram

kW: Kilowatt

kWh: Kilowatt hour

m: Meter

Mg: Mega gram

MJ: Mega joule

mm: Millimetre

m^2: Square meter

m^3: Cubic Meter

µg: Microgram

Scf: Standard Cubic Foot

sej: Solar equivalent joule

Chemical Symbols and Abbreviations

Al: Aluminium

BCM: Bromochloromethane

C: Carbon

Cd: Cadmium

CFC: Chlorofluorocarbon

CH_4: Methane

Cl: Chlorine

CTC: Carbon Tetrachloride

CO_2: Carbon dioxide

CO_X: Carbon oxides

Cu: Copper

DCB: Dichlorobenzene

Fe: Iron

H: Hydrogen

HBFCs: Hydro bromic fluorocarbons

HCFCs: Hydro chlorofluorocarbons

HFCs: Hydro fluorocarbons

Hg: Mercury

MB: Methyl Bromide

N: Nitrogen

N_2O: Nitrous Oxide

NO_X: Nitrogen Oxides

O: Oxygen

O_3: Ozone

PAH: Polyaromatic Hydrocarbons

Pb: Lead

PFCs: Perfluorocarbons

PO: Photochemical oxidation

S: Sulphur

SO_2: Sulphur Dioxide

SO_X: Sulphur Oxides

SF_6: Sulphur Hexafluoride

TCA: Trichloroethane

TEG: Triethylene Glycol

Abbreviations

AD: Anaerobic Digestion

B.S: Basic Scenario

CC: Coarse Compost

CCAP: Climate Change Action Plant

CEAP: Circular Economy Action Plan

CEC: Cumulative Energy Consumption

CEVKO: Environmental Protection and Packaging Waste Recovery and Recycling Foundation (Cevre Koruma ve Ambalaj Atıkları Vakfı)

CF: Characterization Factor

C.S: Combination Scenario

DIN: German Institute for Standardization (Deutsches Institut für Normung)

DOC: Degradable Organic Carbon

DOC_F: Degradable Organic Carbon Fraction

DTU: Technical University of Denmark

EASETECH: Environmental Assessment System for Environmental Technologies

EASEWASTE: Environmental Assessment of Solid Waste Systems and Technology

EC: European Commission

EEA: European Environment Agency

EEC: European Economic Community

EHCIP: Environmental Heavy-Cost Investment Planning

ELV: End of Life Vehicles

EN: European Standards

EP: Eutrophication Potential

EPA: Environmental Protection Agency

EPEM: Environmental Planning and Management

EEG: Renewable Energy Sources Act

EU: European Union

EUROSTAT: European Statistical Office

FAA: Federal Aviation Administration

FC: Fine Compost

FE: Freshwater Eco toxicity

FU: Functional Unit

FW: Food Waste

FYM: Farmyard Manure

GHG: Greenhouse Gas

GHGs: Greenhouse Gases

GWP: Global Warming Potential

HCT: Human Carcinogenic Toxicity

IARC: International Agency for Research on Cancer

ICT: Information and Communication Technologies

IMM: Istanbul Metropolitan Municipality

IMPACT: Impact Assessment of Chemical Toxics

IPCC: Intergovernmental Panel on Climate Change

IPPC: Integrated Pollution Prevention and Control

ISO: International Organization for Standardization

ISTAC: Istanbul Environment Management Industry and Trade Company

ISWA: International Solid Waste Association

ISWM: Integrated Solid Waste Management

ISWMS: Integrated Solid Waste Management System

IWM: Integrated Waste Management

IWMS: Integrated Waste Management Strategies

KIT: Karlsruhe Institute of Technology

LANDGEM: Landfill Gas Emissions Model

LCA: Life Cycle Assessment

LCC: Life Cycle Costing

LCI: Life Cycle Inventory

LCIA: Life Cycle Impact Assessment

LFG: Landfill Gas

LHV: Lower Heating Value

LOI: Loss of Ignition

LU: Land Use

LULUCF: Land Use and Land Use Changes and Forestry

MARSS: Material Advanced Recovery Sustainable Systems

MBR: Membrane Bioreactor

MBT: Mechanical Biological Treatment

MCF: Methane Correction Factor

MENR: Ministry of Energy and Natural Resources

MFA: Material Flow Analysis

MMSW: Mixed Municipal Solid Waste

MOEU: Ministry of Environment and Urban Planning (Türkiye)

MRF: Material Recovery Facility

MSW: Municipal Solid Waste

MSWM: Municipal Solid Waste Management

MSWMS: Municipal Solid Waste Management System

NF: Nanofiltration

ODM: Organic Dry Matter

ODP: Ozone Depleting Potential

ODS: Ozone Depleting Substances

OFMSW: Organic Fraction of Municipal Solid Waste

OLD: Ozone Layer Depletion

ORWARE: Organic Waste Research

PET: Polyethylene Terephthalate

PM: Particulate Matter

PM 2,5: Particulate matter with a diameter less than 2,5 micrometres

PM 10: Particulate matter with a diameter equal or less than 10 micrometres

PMF: Particulate Matter Formation

PO: Photochemical Oxidation

POF: Photochemical Oxidation Formation

RCRA: Resource Conservation and Recovery Act

RDF: Refuse-Derived Fuel

SETAC: Society of Environmental Toxicology and Chemistry

SOD: Stratospheric Ozone Depletion

STAN: Substance Flow Analysis

SWM: Solid Waste Management

TE: Terrestrial Ecotoxicity

TP: Toxicity Potential

TS: Transfer Stations

TURKSTAT: Turkish Statistical Institute

UK: United Kingdom

UNEP: United Nations Environment Programme

UNFCCC: United Nations Framework Convention on Climate Change

USEPA: United States Environmental Protection Agency

w: Water

waf: Water ash free

WEEE: Waste Electrical Electronic Equipment

wf: Water free

WOS: Web of Science

WTE: Waste to Energy

WRAP: Waste and Resources Action Programme

ABSTRACT

Megacities face special challenges in the development and implementation of Municipal Solid Waste Management (MSWM) systems due to their high population density and large waste volumes. These systems need to be environmentally friendly and align with climate and resource protection goals.

Existing and potential future MSWM systems must be evaluated based on these criteria. In this context, there is a lack of an assessment system for megacities, taking into account the current requirements of climate and resource protection, including the European Union's Green Deal. Additionally, this assessment should consider not only the criteria of Life Cycle Assessment (LCA) but also the avoided emissions of fossil greenhouse gases at the regional level through recycling and energy recovery from waste. Unlike previous works, this thesis aims to differentiate material flows, considering collection rates, sorting rates, and residual waste rates at the collection level and within defined facility systems and combinations.

This differentiation will be demonstrated in the case of the Istanbul metropolitan area (Türkiye), where approximately 6,6 million Mg of municipal solid waste are generated annually (based on ISTAC 2020 data). Currently, 83% of this waste is deposited, 11% is composted, and 6% is recycled.

The research questions focus on the ecological assessment of the existing Municipal Solid Waste Management (MSWM) system in the Istanbul metropolitan area and scenarios for future MSWM systems. Basic scenarios are to be developed with the aim of intensifying the recycling and energy recovery of waste. At the same time, the greenhouse gas emissions, primarily caused by landfilling, are to be significantly reduced. In this context, the target goals of the EU regarding recycling and landfill rates are also to be pursued. In combination scenarios, transitional scenarios are to be considered, taking into account the current Municipal Solid Waste Management (MSWM) system in Istanbul and existing plans.

In this thesis, a methodical approach is taken towards mass and energy balances (input-output analyses) using material flow analyses (MFA) (inventory analyses). Here, particular emphasis is placed on the greenhouse gas emissions from waste treatment processes, and for the first time, the substitution of fossil energy sources through waste management measures is examined based on Türkiye energy mix. Additionally, an assessment is conducted using the life cycle assessment (LCA) method. The functional unit is selected as 1 Mg MSW (1 Mega

gram of Municipal Solid Waste), and the characterization results are determined at the midpoint level.

Within this thesis, the following impact categories are considered: Global warming potential (GWP), stratospheric ozone depletion (SOD), freshwater ecotoxicity (FE), terrestrial ecotoxicity (TE), particulate matter formation (PMF), human carcinogenic toxicity (HCT), and land use (LU).

Ten different Municipal Solid Waste Management (MSWM) scenarios are developed, categorized as basic and combination scenarios.

Basic scenarios:

- **B.S-1:** Landfilling of the total MSW
- **B.S-2:** Thermal treatment (incineration) of the total MSW with energy recovery
- **B.S-3:** Metal recycling + thermal treatment (incineration) with energy recovery

B.S-4(a) and B.S-4(b) include waste separation as dry and wet waste at the source:

- **B.S-4(a):** Recycling + composting + anaerobic digestion + landfilling of residual waste
- **B.S-4(b):** Recycling **+** composting + anaerobic digestion + thermal treatment (incineration) of residual waste with energy recovery

B.S-5(a) and B.S-5(b) align with the waste management goals of the EU for 2030, including the separation of organic waste, recycling waste, and residual waste at the source:

- **B.S-5(a):** Recycling + composting + landfilling + thermal treatment (incineration) with energy recovery
- **B.S-5(b):** Recycling **+** anaerobic digestion + landfilling + thermal treatment (incineration) with energy recovery

Combination scenarios:

C.S-1 represents the current situation of the MSWM system in Istanbul:

- **C.S-1:** Recycling **+** composting + landfilling

C.S-2 includes the goals set by the Istanbul municipal government for the year 2023:

- **C.S-2:** Recycling + anaerobic digestion + landfilling + thermal treatment (incineration) with energy recovery

C.S-3 is a transitional scenario that incorporates 50% of the EU targets (2030) for recycling and landfilling:

- **C.S-3:** Recycling **+** composting + landfilling + thermal treatment (incineration) with energy recovery

Based on the calculations of net greenhouse gas (GHG) emissions and net energy generation from the scenarios, the worst scenario is B.S-1 (all of the waste is sent to landfill), which has the highest net GHG emission (908,6 kg CO_2 eq) and the lowest net energy production (92,2 kWh). The second-worst scenario is C.S-1 (current MSWM system), which has the second highest net GHG emission (725,8 kg CO_2 eq) and the second lowest net energy production (364,9 kWh). In contrast, B.S-4(b) has the lowest net GHG emission (50,5 kg CO_2 eq), and it is followed by B.S-5(b) (58,1 kg CO_2 eq) and B.S-5(a) (76,4 kg CO_2 eq). B.S-3 (metal recycling + incineration) has the highest net energy generation (2.040 kWh) and simultaneously the lowest net GHG emission (264,9 kg CO_2 eq) after B.S-4(b), B.S-5(a), and B.S-5(b), respectively.

Taking into account the Türkiye energy mix, the greenhouse gas (GHG) emission coefficient is 0,702 kg CO_2 eq/kWh for electrical energy and 0,219 kg CO_2 eq/kWh for thermal energy. When considering the avoided GHG based on the net heat and electrical energy production according to Türkiye energy mix, only B.S-2, B.S-3, B.S-4(b), B.S-5(a) and B.S-5(b) result in an overall reduction of GHG emissions. B.S-3 performs the best with (240,8 kg CO_2 eq), followed by B.S-4(b) (226 kg CO_2 eq), B.S-2 (197,7 kg CO_2 eq), B.S-5(b) (156,7 kg CO_2 eq), and B.S-5(a) (89,8 kg CO_2 eq), respectively.

According to the LCA calculations results, B.S-5(a) is the best scenario in five out of seven impact categories, which are GWP (-67,74 kg CO_2 eq), FE (66,95 kg 1,4-DCB), TE (-551,08 kg 1,4-DCB), HCT (-14,22 kg 1,4-DCB), and LU (-119,72 m^2a crop area). B.S-5(b) follows B.S-5(a) and has the second-best effect in GWP (-26,28 kg CO_2 eq), FE (74,7 kg 1,4-DCB), TE, (-520,64 kg 1,4-DCB), PMF (-0,91 kg PM 2,5 eq), and LU (-118,66 m^2a crop area) categories. In contrast, B.S-1 is the worst scenario in all impact categories except for SOD category. C.S-1 follows B.S-1 and has the second-worst effect in GWP (651,3 kg CO_2 eq), SOD (-2×10^{-4} kg CFC-11 eq), PMF (-0,19 kg PM 2,5 eq), and LU (-31,78 m^2a crop area).

In summary, both from the perspective of greenhouse gas and energy considerations, as well as life cycle assessment, C.S-1 (Current MSWM System of Istanbul) shows the worst result, followed by B.S-1. B.S-5(a) and B.S-5(b) emerge as the best scenarios in these regards. However, it is noteworthy that these scenarios are only feasible in megacities in emerging countries with the establishment of suitable conditions and require a significant lead time.

Significant investments in collection systems and waste treatment technologies are necessary to achieve high rates of recycling, energy substitution, and a significant reduction in greenhouse gas emissions. Furthermore, citizens must be actively engaged through intensive public awareness campaigns during the introduction of separate collection systems. Essential prerequisites also include the establishment of appropriate legal frameworks and their enforcement.

In this context, the implementation of scenario B.S-4(b) could represent a suitable solution for Istanbul and other megacities in developing countries. In this scenario, separation into wet and dry waste occurs at the source, followed by treatment in biological treatment facilities, sorting facilities, and thermal treatment of residual waste. It is important to consider the aforementioned conditions in this context as well. The environmental impacts of landfilling are significantly reduced, and greenhouse gas emissions are minimized.

The developed scenarios, evaluated from an ecological standpoint, demonstrate, using the example of the greater Istanbul area, that waste management measures can contribute not only to resource conservation but especially to climate protection. Simultaneously, these measures can replace fossil emissions. The chosen approach is also transferable to other megacities, especially in emerging countries.

ZUSAMMENFASSUNG

Megacities stehen unter anderem aufgrund ihrer hohen Bevölkerungsdichte und großen Abfallmengen vor besonderen Herausforderungen bei der Entwicklung und Umsetzung von Systemen zur Siedlungsabfallwirtschaft (MSWM), welche umweltverträglich sind und besonders die Ziele des Klima- und Ressourcenschutzes erfüllen können.

Bestehende und mögliche zukünftige MSWM-Systeme müssen nach diesen Zielkriterien bewertet werden. In diesem Kontext fehlt, unter Berücksichtigung des Standes der Wissenschaft auf Basis der Auswertung der Fachliteratur, für Megacities ein Bewertungssystem, das die aktuellen Anforderungen des Klima- und Ressourcenschutzes, auch vor dem Hintergrund des Green Deal der Europäischen Union, mit einbezieht. In diesem Zusammenhang sollen auch neben den Kriterien der Ökobilanz (LCA) auch die vermiedenen Emissionen fossiler Treibhausgase auf regionaler Ebene durch Recycling und Energieverwertung aus Abfällen betrachtet werden. Im Gegensatz zu bisher publizierten Arbeiten soll zusätzlich eine Differenzierung der Stoffströme unter Berücksichtigung der Erfassungsrate, der Sortierrate und der Restabfallrate auf Ebene der Sammlung und definierter Anlagensysteme und-kombinationen erfolgen.

Dies soll in der vorliegenden Arbeit am Beispiel des Großraumes Istanbul (Türkei) erfolgen. Dort entstehen jährlich ca. 6,6 Mio. Mg Siedlungsabfälle (Basis ISTAC, 2020). Davon werden derzeit 83 % deponiert, 11 % kompostiert und 6 % stofflich verwertet.

Die wissenschaftlichen Fragestellungen befassen sich mit der ökologischen Bewertung des bestehenden MSWM-Systems im Großraum Istanbul und mit Szenarien zu zukünftigen MSWM-Systemen. Basis-Szenarien sollen entwickelt werden, mit dem Ziel das Recycling und die energetische Verwertung von Abfällen zu intensivieren. Gleichzeitig sollen die vor allem durch die Deponierung verursachten Treibhausgasemissionen deutlich verringert werden. Hierbei sollen auch die Zielgrößen der EU hinsichtlich der Recycling- und Deponiequoten angestrebt werden. In Kombinationsszenarien sollen Übergangsszenarien unter Berücksichtigung des derzeitigen MSWM-Systems in Istanbul und der existierenden Planungen betrachtet werden.

Methodisch wird in der vorliegenden Arbeit über Massen- und Energiebilanzen (Input-Output-Analysen) unter Einsatz von Materialflussanalysen (MFA) vorgegangen (Sachbilanzen). Hierbei sollen besonders Klimagasemissionen der Abfallbehandlungsverfahren und erstmalig die Substitution fossiler Energieträger durch abfallwirtschaftliche Maßnahmen auf Basis des Energiemix der Türkiye betrachtet werden.

Darüber hinaus erfolgt eine Bewertung nach der Methode der Ökobilanz (LCA). Als funktionale Einheit werden 1 Mg MSW ausgewählt und die Charakterisierungsergebnisse auf der MapPoint-Ebene ermittelt.

Im Rahmen dieser Untersuchung werden folgende Wirkungskategorien betrachtet: das globale Erwärmungspotenzial (GWP), der stratosphärische Ozonabbau (SOD), die Süßwasser-Ökotoxizität (FE), die terrestrische Ökotoxizität (TE), die Feinstaubildung (PMF), die Human krebserzeugende Toxizität (HCT) und die Landnutzung (LU).

Es werden zehn verschiedene MSWM-Szenarien entwickelt, die als Grund- und Kombinationsszenarien kategorisiert werden.

Basis-Szenarien:

- **B.S-1:** Deponierung des gesamten MSW
- **B.S-2:** Thermische Behandlung (Verbrennung) des gesamten MSW mit Energienutzung
- **B.S-3:** Metallrecycling + thermische Behandlung (Verbrennung) des verbleibenden Abfalls mit Energienutzung

B.S-4(a) und B.S-4(b) beinhalten die getrennte Erfassung von trockenem und nassem Abfall an der Quelle

- **B.S-4(a):** Recycling + Kompostierung + anaerobe Vergärung + Deponierung des Restabfalls
- **B.S-4(b):** Recycling + Kompostierung + anaerobe Vergärung + Verbrennung des Restabfalls mit Energienutzung

B.S-5(a) und B.S-5(b) entsprechen den Abfallbewirtschaftungszielen der EU für das Jahr 2030 mit Trennung von Bioabfall, Recyclingabfall und Restabfall an der Quelle;

- **B.S-5(a):** Recycling + Kompostierung + Deponierung + thermische Behandlung (Verbrennung) mit Energienutzung
- **B.S-5(b):** Recycling + anaerobe Vergärung + Deponierung + thermische Behandlung (Verbrennung) mit Energienutzung

Kombinations-Szenarien:

C.S-1 stellt die aktuelle Situation des MSWM-Systems in Istanbul dar;

- **C.S-1:** Recycling + Kompostierung + Deponierung

C.S-2 beinhaltet die Ziele für das Jahr 2023 der Istanbuler Stadtverwaltung;

- **C.S-2:** Recycling + anaerobe Vergärung + Deponierung + thermische Behandlung (Verbrennung) mit Energienutzung

C.S-3 ist ein Übergangsszenario, das 50 % der EU-Zielwerte (2030) für Recycling und Deponierung beinhaltet.

- **C.S-3:** Recycling + Kompostierung + Deponierung + thermische Behandlung (Verbrennung) mit Energienutzung

Basierend auf den Berechnungen der netto erzeugten THG und der netto erzeugten Energie der Szenarien ist das schlechteste Szenario B.S-1 (gesamter Abfall wird zur Deponie gebracht) mit der höchsten Netto-THG-Emission (908,6 kg CO_2 eq) und der niedrigsten Netto-Energieproduktion (92,2 kWh). Das zweitschlechteste Szenario ist C.S-1 (aktuelles MSWM-System), das nach B.S-1 die höchste Netto-THG-Emission (725,8 kg CO_2 eq) und die zweit-niedrigste Netto-Energieproduktion (364,9 kWh) aufweist. Im Gegensatz dazu weist B.S-4(b) mit (50,5 kg CO_2 eq), die geringste Netto-THG-Emission auf, gefolgt von B.S-5(b) (58,1 kg CO_2 eq) und B.S-5(a) (76,4 kg CO_2 eq) auf den nächsten Plätzen. B.S-3 (Metallrecycling + Verbrennung) beinhaltet die höchste Netto-Energie-Substitution (2.040 kWh) und gleichzeitig die niedrigste Netto-THG-Emission (264,9 kg CO_2 eq) nach B.S-4(b), B.S-5(a) und B.S-5(b).

Unter Berücksichtigung des Energiemix der Türkiye beträgt der THG-Emissionskoeffizient für elektrische Energie 0,702 kg CO_2-Äquivalente/kWh und für Wärmeenergie 0,219 kg CO_2-Äquivalente/kWh. Werden unter diesem Ansatz nur die Szenarien betrachtet, durch die insgesamt eine Vermeidung von THG-Emissionen erzielt wird, so schneidet das Szenarium B.S-3 mit (240,8 kg CO_2 eq) am besten ab, gefolgt von B.S-4(b) (226 kg CO_2 eq), B.S-2 (197,7 kg CO_2 eq), B.S-5(b) (156,7 kg CO_2 eq), und B.S-5(a) (89,8 kg CO_2 eq).

Gemäß den Ergebnissen der Ökobilanzberechnung ist B.S-5(a) das beste Szenario in fünf von sieben Wirkungskategorien, nämlich GWP (-67,74 kg CO_2 eq), FE (66,95 kg 1,4-DCB), TE (-551,08 kg 1,4-DCB), HCT (-14,22 kg 1,4-DCB), und LU (-119,72 m^2a Anbaufläche). B.S-5(b) folgt B.S-5(a) und hat den zweitbesten Effekt in den Kategorien GWP (-26,28 kg CO_2 eq), FE (74,7 kg 1,4-DCB), TE (-520,64 kg 1,4-DCB), PMF (-0,91 kg PM 2,5 eq) und LU (-118,66 m^2a Anbaufläche). Im Gegensatz dazu ist B.S-1 das schlechteste Szenario in allen Wirkungskategorien, außer in der Kategorie SOD. C.S-1 folgt B.S-1 und hat den zweitschlechtesten Effekt in den Kategorien GWP (651,3 kg CO_2 eq), SOD (-2 x 10^{-4} kg CFC-11 eq), PMF (-0,19 kg PM 2,5 eq), und LU (-31,78 m^2a Anbaufläche).

Zusammenfassend zeigt sich, dass sowohl auf Basis der GHG- und Energiebetrachtungen als auch der Ökobilanzierung C.S-1 (Aktuelles MSWM-System von Istanbul) das schlechteste Ergebnis zeigt, gefolgt von B.S-1. B.S-5(a) und B.S-5(b) sind unter diesen Aspekten die besten Szenarien. Hierbei ist jedoch festzustellen, dass diese Szenarien in Megastädten in Schwellenländern nur bei Schaffung geeigneter Rahmenbedingungen umsetzbar sind und einen langen zeitlichen Vorlauf brauchen. Es müssen erhebliche Investitionen in Sammelsysteme und Abfallbehandlungstechnologien gemacht werden, um die hohen Raten für Recycling und Energiesubstitution sowie eine deutliche Verringerung an Treibhausgasemissionen zu erreichen. Weiterhin müssen die Bürgerinnen und Bürger bei der Einführung von Getrennten Sammelsystemen durch intensive Öffentlichkeitsarbeit einbezogen werden. Voraussetzungen sind auch die entsprechenden gesetzlichen Rahmenbedingungen und deren Vollzug.

Vor diesem Hintergrund kann die Umsetzung des Szenarios B.S-4(b), eine geeignete Lösung für Istanbul und andere Megastädte in Schwellenländern darstellen. Hierbei erfolgt die Trennung in feuchte und trockene Abfälle an der Anfall stelle mit anschließender Behandlung in biologischen Behandlungsanlagen, Sortieranlagen und einer thermischen Behandlung der Restabfälle. Auch hier sind die oben genannten Randbedingungen zu beachten. Die Umweltauswirkungen der Deponierung werden deutlich verringert und die Emission von Treibhausgasen minimiert.

Die entwickelten und unter ökologische Gesichtspunkten bewerteten Szenarien zeigen am Beispiel des Großraumes Istanbul, dass abfallwirtschaftliche Maßnahmen nicht nur zum Ressourcenschutz, sondern besonders auch zum Klimaschutz beitragen können. Gleichzeitig können hierbei fossile Emissionen ersetzt werden. Die gewählte Vorgehensweise ist auch auf andere Megacities, besonders in Schwellenländern, übertragbar.

1. PROBLEM STATEMENT

Increases in populations, living standards, technological developments, industrialization, and urbanization lead to an increase in consumption. In addition to food, this also includes packaging, household appliances, and items, information technology equipment and clothing. Environmental problems have also rapidly increased in direct proportion to these needs. Solid wastes are non-liquid wastes that are derived from anthropogenic activities. They contain organic and inorganic components such as product wrapping, grass residue, bottles, wastepaper, paint, cans, and batteries (Ramachandra, 2006).

The negative impacts of solid waste on soil, water, air, and most importantly, health are due to its random accumulation in open spaces. There are negative effects on the environment in terms of biological, chemical, and physical properties. MSW is considered one of the main sources of energy consumption, urban degradation, and pollution. Waste management plans are fundamental to increase the ability of urban areas to effectively adapt to waste challenges. These plans must outline waste streams and treatment options while providing a scenario for the following years that significantly reduces landfills and incinerators in favour of prevention, reuse, and recycling. If solid waste is not managed correctly, it may be responsible for air pollution, flooding, and public health impacts, such as respiratory ailments (TeMA, 2016).

Improperly managed solid waste poses a risk to human health and the environment. Uncontrolled dumping and improper waste handling cause a variety of problems, such as water contamination, attracting insects and rodents, and increasing flooding due to blocked drainage canals or gullies. Additionally, it may result in safety hazards from fires or explosions. Improper waste management also increases GHG emissions, contributing to climate change. Planning for and implementing a comprehensive program for waste collection, transport, and disposal along with activities to prevent or recycle waste, can eliminate these problems (USEPA, 2002).

The negative effects of improper waste management not only result in a displeasing view but also affect the overall economy of a country. The state must spend a significant amount of money to counter the effects of improper waste management. Moreover, animals dependent on the environment also face a great threat due to the oil spills and leaching of chemicals that directly cause soil and water contamination. Burning disposed waste and plastic materials also results in air and environmental pollution (UNEP, 2009).

MSW generation was 2,01 billion Mg/y in 2016 worldwide, and at least 33% of this waste was not managed properly (Kaza et. al, 2018). The global amount of waste is expected to reach 3,40 billion Mg/y by 2050, and a third of this waste is dumped or burned. Particularly, megacities, which are metropolitan areas with a total population of more than 10 million, face an increasing challenge in the MSWM due to rapid urbanization and economic development. This creates great pressure on megacities, especially regarding land scarcity, food waste, and resource recovery (Zhou et al., 2022).

According to the World Population Review, the number of megacities is 32 by the year 2022 (Table 1).

Table 1. Megacities of the world in 2022 (World Population Review, 2022)

	City	Country	Population
1	**Tokyo**	Japan	37.274.000
2	**Delhi**	India	32.065.760
3	**Shanghai**	China	28.516.904
4	**Dhaka**	Bangladesh	22.478.116
5	**Sao Paulo**	Brazil	22.429.800
6	**Mexico City**	Mexico	22.085.140
7	**Cairo**	Egypt	21.750.020
8	**Beijing**	China	21.333.332
9	**Mumbai**	India	20.961.472
10	**Osaka**	Japan	19.059.856
11	**Chongqing**	China	16.874.740
12	**Karachi**	Pakistan	16.839.950
13	**Istanbul**	Türkiye	15.636.243
14	**Kinshasa**	Democratic Republic of the Congo	15.628.085
15	**Lagos**	Nigeria	15.387.639
16	**Buenos Aires**	Argentina	15.369.919
17	**Kolkata**	India	15.133.888
18	**Manila**	Philippines	14.406.059
19	**Tianjin**	China	14.011.828
20	**Guangzhou**	China	13.964.637
21	**Rio De Janeiro**	Brazil	13.634.274
22	**Lahore**	Pakistan	13.541.764
23	**Bangalore**	India	13.193.035
24	**Shenzhen**	China	12.831.330
25	**Moscow**	Russia	12.640.818
26	**Chennai**	India	11.503.293
27	**Bogota**	Colombia	11.344.312
28	**Paris**	France	11.142.303
29	**Jakarta**	Indonesia	11.074.811
30	**Lima**	Peru	11.044.607
31	**Bangkok**	Thailand	10.899.698
32	**Hyderabad**	India	10.534.418

The amount of waste generation in the megacities corresponds to 11% of the waste generation in the world. Currently, 4,9 million Mg/d of MSW (2,6 million Mg/d of organic waste) is generated worldwide, while 0,59 million Mg/d of MSW (0,3 million Mg/d of organic waste) is generated in the megacities (ISWA, 2020).

Another issue of global interest is the expected increase in the organic fraction of waste in the megacities. If present waste management trends are maintained, it is estimated that landfilled food waste will increase global CH_4 emissions from 34 to 48 million Mg/y and landfill share of global anthropogenic emissions rise from 8% to 10% between 2005-2025. Another problem in urban areas is the role of the informal sector in waste management, both in Istanbul and many other megacities. The main activity of the informal sector in solid waste management is the recycling and recovery of materials. This activity diverts a significant amount of materials from disposal and supports the livelihoods of millions of poor people (Mavropoulos, ISWA 2010).

When investigating the waste disposal systems used in the world, it is observed that megacities located in developed countries utilize waste reduction, recovery/recycling, landfilling, thermal, and biological processes. These methods are preferred depending on the requirements of the disposal area, economic and cultural levels, and country policies.

The amount of the landfilled waste has exceeded the estimated waste capacity in many megacities located in developing countries such as Lagos (13.000 Mg/d), Mumbai (11.000 Mg/d), Manila (9.000 Mg/d), and Jakarta (7.000 Mg/d) (Harris, 2020). Landfilling is the most commonly used waste disposal method in Istanbul and Türkiye. 83% (69,43%) of the collected municipal waste is disposed of through the landfill process, the composting rate is equal to 11% (0,36%) of the waste, and the recovered/recycled rate corresponds to 6% (12,83%) of the waste in Istanbul (Türkiye) (ISTAC, 2020).

The main shortcomings of municipal solid waste management in Istanbul are the incomplete application of the 3Rs (reduce, reuse, and recycle) of the waste management hierarchy. Within the scope of waste generation reduction and recycling/recovery activities, the incentive system for reducing the waste produced and using clean technologies is not sufficient. Although the total municipal solid waste includes approximately 30% of recoverable qualified waste (plastic, paper, glass, metal, etc.), only 6% of the waste is recycled in the city (IMM, 2020). The prominent problems are the failure of the separate collection system at its source, the absence of a sufficient number of separation facilities throughout Istanbul, and the lack of the number and capacity of recycling and recovery facilities.

The development of the "reuse, reduce, and recycle", which are the main circular economy principles, guarantees energy and raw material saving, waste recycling, and reduces carbon emissions. The increase in waste recycling and restricted use of landfills will reduce environmental impacts, save energy resources, and improve economic impacts (Allevi et al., 2021).

2. GOAL AND SCOPE DEFINITION AND STATE OF KNOWLEDGE

2.1. Introduction

MSW is an important source of greenhouse gases, and it rank as the fourth-largest GHG emission sector, contributing to 3% of total greenhouse gas emissions in 2017 (Eurostat, 2020). Based on the IMM GHG inventory report, Istanbul released 50,9 Mio Mg CO_2 eq (3,3 Mg CO_2 eq per capita) of emissions by 2019. The stationary energy use in buildings, manufacturing, and construction constitutes 63% of the total GHG emissions. The transportation sector follows with 28% of the total emissions, and the waste sector (landfill disposal, composting, industrial incineration, and wastewater) causes 9% of the emissions (Istanbul CCAP, 2021).

If the GHG emissions caused by waste and wastewater sectors are not decreased, it is estimated that this contribution will quadruple by 2050. A significant proportion of the greenhouse gases from the waste sector is methane, which has 25 times higher global warming potential than carbon dioxide. The vast majority of this methane emission originates from MSW management practices. According to the official reporting of the United Nations Framework Convention on Climate Change (UNFCC), the percentage of greenhouse gas emissions from solid waste disposal methods is divided into three subcategories: 95% from landfill without energy recovery, 3% from incineration, and 2% from other treatments such as fermentation/composting (UNFCC, 1992).

Sustainable solid waste management is one of the major challenges worldwide. Inadequate collection, recycling, or treatment, and uncontrolled waste disposal in dumping lead to severe hazards, such as health risks and environmental pollution. This situation is especially serious in developing countries where inadequate waste disposal can be very dangerous (Garfi et. al., 2009).

These problems are also major challenges in Istanbul, making it difficult to manage municipal solid waste, especially considering the high population density and population growth rate. Istanbul megacity is the largest city in Türkiye, with a population of 14,8 million people, and the fifth-largest city in the world in terms of population within city limits. The city produces 18.100 Mg of solid waste per day, equivalent to 6.606.500 Mg of waste annually. 83% of the produced municipal waste is disposed of in landfills, 11% goes to composting plants, while 6% of the waste is recycled in the city (ISTAC, 2020).

The increase in the amount of waste and constant disposal of the vast majority of waste in landfills create the need for new areas, which is not a sustainable waste management option. Furthermore, MSW management has been a pressure point for Türkiye as it is a candidate country for EU accession (TCA, 2007). This requires the implementation of alternative disposal systems that will reduce the amount of waste disposed of in landfills.

2.2. Goal and Scope of the Thesis

The thesis aims to evaluate the current MSWM of Istanbul and different alternative waste management scenarios to determine the best management option for the megacity in terms of climate change, ecosystem quality, and human health to minimize the negative impacts of the landfill process, to assess the energy efficiency of the disposal process and the scenarios, and to realize the solid waste strategic targets for Türkiye according to the EU integration process.

In this context, the current MSWMS of Istanbul is determined, LCA study is conducted on the MSWMS of Istanbul, and created solid waste management options which include the different percentage of the landfilling, composting, anaerobic digestion, and incineration methods under the categories of basic and combination scenarios.

Basic scenarios:

- **B.S-1:** Landfilling (All of collected MSW disposed of with landfill)
- **B.S-2:** Incineration (All of collected MSW disposed of with thermal treatment (incineration) with energy recovery)
- **B.S-3:** Recycling of metal parts + thermal treatment (incineration) with energy recovery
- **B.S-4(a):** Recycling + composting + anaerobic digestion + landfilling (Waste separation as dry and wet waste in source and landfilling of residual waste)
- **B.S-4(b):** Recycling + composting + anaerobic digestion + incineration (Waste separation as dry and wet waste in source and thermal treatment (incineration) of residual waste with energy recovery)
- **B.S-5(a):** Recycling + composting + landfilling + thermal treatment (incineration) with energy recovery (Based on EU 2030 waste management targets including the composting process for biowaste)

- **B.S-5(b):** Recycling + anaerobic digestion + landfilling + thermal treatment (incineration) with energy recovery (Based on EU 2030 waste management targets including anaerobic digestion process for biowaste)

Combination scenarios:

- **C.S-1:** Recycling + composting + landfilling (Current MSWM of Istanbul)
- **C.S-2:** Recycling + anaerobic digestion + landfilling + thermal treatment (incineration) with energy recovery (MSWM targets of Istanbul Metropolitan Municipality)
- **C.S-3:** Recycling + composting + landfilling + thermal treatment (incineration) with energy recovery (Transition MSWM scenario applicable to Istanbul currently)

The input and output analyses are performed by calculating the mass and energy balances of the disposal processes and the scenarios. In the next step, GHG emissions, the amount of avoided GHG and avoided energy obtained from recycling, composting, and anaerobic digestion processes are calculated. The amounts of net GHG and net energy productions are determined (Fig. 1). In this LCA analysis, Recipe, 2016 (Hierarchist, 100 years of time horizon) impact assessment method is used with the 9.3.0.3 version of the SimaPro. The functional unit is selected as 1 Mg of MSW, and characterization results are obtained at the midpoint level.

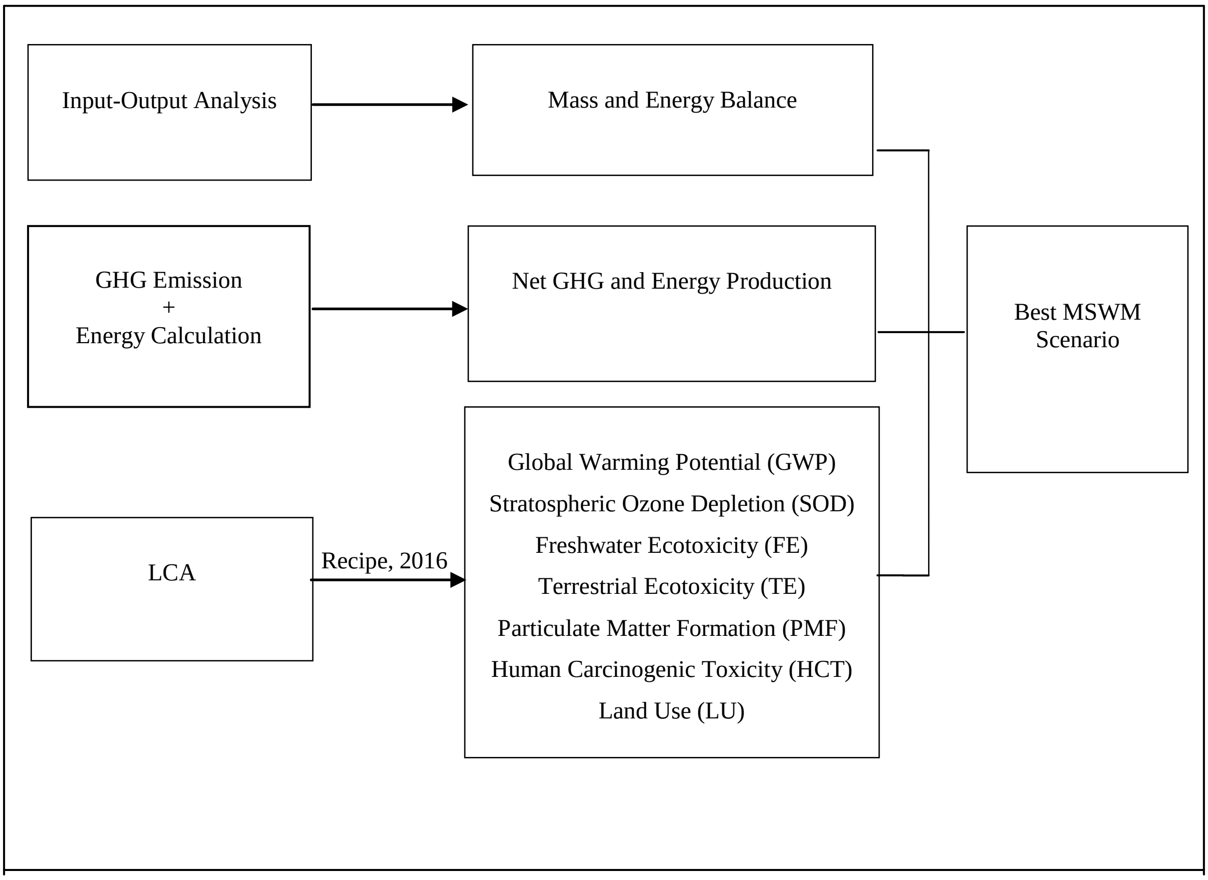

Figure 1. Scope of the Thesis

2.3. Research Questions

Istanbul is one of the most important megacities with 84.680 thousand inhabitants in 2021, which exceeds the population of many countries in the world. Approximately, 18,6% of Türkiye's population resides in Istanbul.

Megacities significantly impact various living conditions for citizens. Despite worsening traffic congestion, declining air quality, and increasing health risks, many people choose to live in these urban centres. Climate change, waste management problems, and energy supply are among the major challenges faced by megacities. GHG emissions from industry, transport, and agriculture are likely the main cause of the observed global warming. Waste management is another significant challenge for megacities as they must handle large quantities of waste daily, requiring extensive logistics for proper disposal. Moreover, most of the megacities are located in developing and emerging countries, which often lack the legal and financial capacity to cope with rapid urban growth. As a result, organized waste collection process may be lacking due to financial constraints. Energy supply poses another problematic issue in megacities. The lack of infrastructure and heavy reliance on fossil fuels, especially in developing and emerging countries, significantly increases air pollutants like GHG, sulphur, and nitrogen oxides. Therefore, the utilization of energy-efficient technologies that use renewable energy sources is crucial to mitigate the negative effects of fossil fuel use while meeting the growing energy demands of the population (Makinde, 2012).

Megacities face tremendous environmental challenges and threats to human health. In this context, the role of waste management is becoming increasingly crucial, both for daily life and for the long to medium-term sustainability of these urban centres. The challenge of successful waste management in megacities is one of the most demanding tasks for public authorities and the waste management industry. One frequent problem is the collection of information regarding the various stakeholders involved in the waste management system. Additionally, understanding the material and resource flow in a megacity poses a significant challenge in any large urban centre, especially in developing and emerging countries, due to the complexity of the system. Furthermore, the difficulty of the task is compounded by the fact that a large part of the waste and resources are managed and recovered informally or at the interface between the informal and formal sectors (Escalante, 2010 and Mavropoulos, 2010).

In addition, the challenges in finding suitable locations for landfilling waste in Istanbul megacity necessitate the establishment of alternative technologies in waste management. The lack of space for storage and the failure to meet the requirements for organic waste storage in accordance with the legislation bring thermal disposal technologies to the forefront of waste management.

However, despite the shortage of integrated solid waste management systems in the province, landfilling remains indispensable. Regardless of the disposal technology used (incineration, composting, etc.), the landfill is needed as the final process. Composting, anaerobic digestion, and incineration technologies should be included in the integrated waste management system to reduce the amount of waste deposited in landfills and to ensure the use of existing storage areas for many years, in compliance with national and EU legislation, to meet the targets for organic waste.

This thesis aims to answer the following research questions related to the solid waste management system for Istanbul megacity, Türkiye’s largest city, using the LCA tool:

- What are the environmental effects of the current MSWM system of Istanbul? How can these effects be reduced?
- Which disposal system and/or systems can be used to reduce the load of the landfill?

- How can GHG emissions be reduced in the scope of Türkiye's compliance with the European Union (EU) Green Deal?
- How can 65% of the MSW recycling rate be achieved by 2030?
- What is the best municipal solid waste management strategy in terms of climate change, ecosystem quality, and human health?
- Which disposal process and MSWM strategy have the highest energy efficiency?
- What is the most applicable MSWM strategy to accomplish the solid waste management strategy for the EU integration process?

2.4. Novelty of the Thesis

2.4.1. General Introduction

To assess the novelty of the thesis, a search for scientific publications in scientific databases is conducted.

In the first step, scientific publications related to SWM are searched in the Web of Science. The goal of this step is to find the publications containing the keyword "LCA" in the title, abstract, or keywords. Accordingly, sources are collected by searching for the keywords "LCA" in the title, abstract, or keywords. The first publication related to LCA was published in 1992. Over time, the number of publications reached 35.103 by the year 2022, 460 of these publications were produced by scientists in Türkiye. To further elaborate on the findings, the keyword "Waste Management" is added to the search. As a result, there are 2.362 publications containing both keywords, of which 43 papers are produced in Türkiye. It is observed that some of these publications are related to agriculture, while others are related to industry and construction wastes.

In the second step of the search process, the literature review is further detailed, and the keyword "MSWM" is added to "LCA" for a more specific search. According to the findings, a total of 258 publications are found between 2004 and 2022 worldwide. Next, LCA studies on MSWM in Istanbul and other megacities are specifically searched using the Web of Science (WOS) database. The outcomes of the literature survey are presented in Table 2. In the following steps of the search, the keywords in the "Waste" and "LCA" categories are used in conjunction with the "Megacities" and "Istanbul" keywords separately. Additionally, the keywords in the "Input-Output Analysis" category are used with the "Megacities" and "Istanbul" keywords separately. It is observed that, although Istanbul is a megacity, the publications searched with the "Istanbul" keyword outnumber the publications searched with the "Megacities" keyword in the literature. The reason behind this is that the specific term “Megacities” may not be commonly used in publications related to megacities, leading to a more detailed literature review. For the new search, the Web of Science database is used to conduct an updated search.

Table 2. Number of Publications in the Waste, LCA and Input-Output Analysis Categories (WOS, 2022)

Keywords	**Publication Number**
WM + Megacities	43
WM + Istanbul	92
SWM + Megacities	19
SWM + Istanbul	26
MSWM + Megacities	6
MSWM + Istanbul	4
LCA	
LCA	35.103
LCA + WM	2.362
LCA + WM + Megacities	6
LCA + WM + Istanbul	5
LCA + SWM + Megacities	3
LCA + SWM + Istanbul	2
LCA + MSWM + Megacities	0
LCA + MSWM + Istanbul	0
Input-Output Analysis	
Input-Output Analysis + WM + Megacities	0
Input-Output Analysis + WM + Istanbul	0
Input-Output Analysis + SWM + Megacities	0
Input-Output Analysis + SWM + Istanbul	0
Input-Output Analysis + MSWM + Megacities	0
Input-Output Analysis + MSWM + Istanbul	0

2.4.2. Municipal Solid Waste Management (MSWM) in the Megacities

Megacities are a product of continuous urbanization, typically defined as a metropolitan areas with a total population of more than 10 million people. They stand apart from global cities due to their rapid growth. However, the substantial growth of megacities also brings forth tremendous environmental challenges and threats to human health. In this context, waste management plays and increasingly crucial role in the daily life and long to medium-term sustainability of megacities. Successfully managing waste in these densely populated urban centres poses one of the most demanding challenges for human societies, especially for the waste management industry (Mavropoulos, 2010).

The majority of megacities are located in developing and emerging countries, with only three megacities which are Tokyo (Japan), Osaka (Japan), and Paris (France) found in economically developed countries. Table 2 clearly shows that China and India have the greatest number of megacities, with 6 each out of the total 32. Among all megacities, Tokyo stands as the world's most populous, followed by Delhi (India) and Shanghai (China), respectively. Istanbul, with over 15 million residents, is the most populous city in Europe, followed by Moscow (over 12 million) and Paris (11 million) (World Population Review, 2022).

The current and future MSWM in developing and emerging countries megacities are often characterized by a disposal-oriented mind-set, with little emphasis on resource recovery and environmental protection, in contrast to MSWM in developed countries. Due to the absence of source separation practices, waste is collected in mixed form and transported to dumpsites or substandard landfills. At these disposal sites, landfill gas and leachate management are limited, resulting in significant impact on the local environment and global climate (Escalante, 2010).

The negative effects of improper waste management not only result in a disgusting view but also affect the overall economy of a country. Local administrations (municipalities) must spend a lot of money to counter the effects of improper waste management. In addition, animals dependent on the environment also face a great threat due to the oil spills and leaching of chemicals, which directly cause soil and water contamination. The burning of any disposed waste and plastic materials results in air and environmental pollution (MTS, 2017).

World Population Review (2022) has categorized the countries into four groups based on income levels. These groups are high-income (developed) countries, lower-middle-income and upper-middle-income (developing) countries, as well as low-income countries. For a more detailed analysis, the megacities in Table 1 are categorized according to the income levels of the countries where they are located (Table 3).

Table 3. Classification of Megacities by Income Levels (World Population Review, 2022)

High-Income (Developed) Countries	
Paris	France
Tokyo, Osaka	Japan
Upper Middle-Income (Developing) Countries	
Buenos Aires	Argentina
Sao Paulo, Rio De Janeiro	Brazil
Shanghai, Beijing, Chongqing, Tianjin, Guangzhou, Shenzhen	China
Bogota	Colombia
Mexico City	Mexico
Lagos	Nigeria
Lima	Peru
Moscow	Russia
Bangkok	Thailand
Istanbul	Türkiye
Lower Middle-Income (Developing) Countries	
Dhaka	Bangladesh
Kinshasa	Democratic Republic of Congo
Cairo	Egypt
Delhi, Hyderabad, Mumbai, Kolkata, Bangalore, Chennai	India
Jakarta	Indonesia
Karachi, Lahore	Pakistan
Manila	Philippines

MSW generation and disposal rates vary according to the income levels of the countries. High-income countries generate 34% of the world's waste, upper-middle-income and lower-middle-income countries generate 32% and 29% of the global waste, respectively, while 5% of the waste is generated in low-income countries. However, lower-middle-income countries are likely to experience the greatest growth in waste production because of economic development and population growth. Open dumping is the most widely used waste disposal method in lower-middle-income country megacities, while the landfill is the main disposal process in the upper-middle-income (developing) country megacities. Despite that, megacities located in high-income countries focus on recovering materials with recycling and composting methods and energy production with an incineration process (Table 4) (Kaza et al., 2018).

Table 4. MSW Disposal Methods in Megacities by Income Levels (Kaza et al., 2018)

Countries by Income Levels	Open dumping	Landfill	Recycling	Composting	Incineration	Other Advanced Disposal
	%					
High-Income	2	39	29	6	22	2
Upper Middle-Income	30	54	4	2	10	-
Lower Middle-Income	66	18	6	10	-	-

In China MSW generation was 228 Million Mg in 2018, 52% of the MSW disposed of with the landfill process, while 45% of the waste was incinerated, and 3% of the waste was composted (Khan et al., 2022). Source separation and waste collection have been actualized in China since 2000, but no efficient results have been achieved. Waste classification became mandatory in April 2019, and most of the cities in the country have gradually implemented waste classification (Sicab, 2020). The Ministry of Housing and Urban-Rural Development issued the Classification Signs of Domestic Garbage standard in China in 2019. As a result of this mandatory implementation, 46 cities, including Shanghai, Beijing, Chongqing, Tianjin, Guangzhou, and Shenzhen megacities in China have started MSW classification and created disposal system. MSW is adjusted to be categorized into four main categories: kitchen waste, recyclable, hazardous waste, and residual waste (Chensi et al., 2019).

Shanghai is the biggest city in China and the third most populous city in the world. However, it is the first city in China to have completely implemented waste classification. After, the 2019 Shanghai Municipal Waste Management Regulation was enacted, waste was separated into four categories as food waste, recyclable, hazardous, and residual waste. As of 2020, 7.000 Mg of recyclable waste, 9.000-10.000 Mg of food waste, 15.000-16.000 Mg of residual waste, and 3,3 Mg of hazardous waste collected per day in Shanghai. Food waste disposal rates comprised 45% for anaerobic digestion, 38% for incineration, and 17% for the composting process. Simultaneously, 18% of the collected residual waste was landfilled, while 82% of it was incinerated (Li et. al., 2021).

Beijing, the capital city of China, had an MSW production of 10,11 million Mg, and its MSW disposal process consisted of 45% landfill, 43% incineration, and 12% composting by 2019 (He et al., 2021).

According to Laohalidanond et al. (2015), approximately 9.930 Mg/d of MSW is generated in Bangkok, the capital and the most populous city of Thailand. This value corresponds to 1,18 kg/d per person in 2013. They stated that Bangkok currently has no WTE plant in operation, and most of the collected MSW is disposed of in a landfill, similar to the MSWM process in Beijing and Hong Kong.

Based on the study performed by Saifullah and Islam (2016), the MSW generation in the Dhaka megacity of Bangladesh is 4.634 Mg/d. Unfortunately, there is no available system for source separation of waste and hazardous waste collection, and disposal in the city. The lack of policy implementation acts as a barrier to the formalized recycling sector. The proportion of organic waste (food waste) is the highest in the total waste similar to other developing countries. Open dumping and landfilling are the most common MSW disposal process in the city.

Ermoleava et al. (2019) evaluated the social factors of waste management in Moscow, a megacity in Russia, and Sao Paulo, a megacity in Brazil. It was determined that these two megacities have similar waste generation rates (402 kg of waste per person annually). Moscow's waste is composed of 24,7% organic waste, 24,3% paper-cardboard, 11,4% glass, 16,2% plastics, and 23,4% others, while Sao Paulo's waste is composed of 47% organic waste, 16% paper, 1% glass, 10% plastic, 2% metal, 1% rubber, and 22% other waste. The recycling rate was determined as 5-7% for all recyclable fractions in Moscow. In contrast, Sao Paulo's waste recycling rate is determined as 98% for aluminium cans, 75% for cardboard, 47% for steel cans, 29% for paper, 22% for plastics, 45% for glass, 85% for tyre and 57% for PET. Jürgensen (2019) stated that the MSW management of Sao Paulo consists of collection, transportation, and final disposal in two sanitary landfills with biogas capture, without any pre-treatment option.

On the other hand, Kurbatova and Abu Qdais (2020) determined that 11 million tons of MSW are generated in Moscow, Russia's megacity. This value corresponds to 18,5% of the MSW generated in the country. Similarly, more than 90% of the generated MSW is finally disposed of in open dumps and sanitary landfills.

In Tokyo, which is the largest city in Japan and the most populous city of the world, approximately 3 million Mg of MSW is generated annually. 70% of the generated waste arises from households, while the other 30% of the waste originates from the business sector. The megacity has only one operating landfill, and the largest amount of disposed waste is incineration residue, followed by municipal waste (Luk, 2021).

Mandpe et al. (2022) stated that the MSW generation rate is approximately more than 7.000 Mg/d in Delhi. The MSW consists of 6,6% paper, 4% textile, 0,6% leather, 1,5% plastics, 2,5% metals, 1,2% glass, 31,78% compostable waste, and 51,5% ash, fines, and others. 5.730 Mg of the waste is landfilled, 430 Mg of the waste is composted, and 560 Mg of the waste is recycled in Delhi, for the year 2017. It is also determined that there are three sanitary landfill plants and two composting plants in operation, while the WTE plants are not operational in Delhi currently.

2.4.3 LCA Studies on Municipal Solid Waste Management (MSWM) in the Megacities

In the final step of the search, the literature review on LCA studies for MSWM is limited solely to megacities around the world. A total of 11 publications related to LCA on MSWM in megacities are found. In the second step of the search, the literature review on LCA studies for MSWM is limited solely to Istanbul. The findings show that there are only 3 publications related to LCA on MSWM for Istanbul. Out of these studies, 2 study are conducted on packaging waste, while one study is performed on food waste (Table 5).

Table 5. LCA Publications on MSWM in the Megacities (Science Direct, 2022)

	Megacities	References	Parameters	Waste Type/Process
1	Sao Paulo	Mendes et. al., (2003)	Global warming, acidification, and nutrient enrichment	Simply biodegradable fraction of MSW
2	Chennai	Jha et al., (2008)	GHG emissions	Landfill sites
3	Tianjin	Zhao et al., (2009)	GHG emissions	Current and possible MSWM strategies
4	Delhi	Bohra et al., (2012)	GWP	MSWM strategies
5	Rio de Janeiro	Angelo et al., (2016)	Environmental impacts	Food waste management
6	Istanbul	Yıldız-Geyhan et al., (2016)	Environmental impacts	Packaging waste management
7	Rio de Janeiro	Saraiva et al., (2017)	Environmental impacts	Three MSWM alternatives for organic fraction of MSW
8	Beijing	Liu et al., (2017)	Total emergy use	MSWM strategies
9	Istanbul	Guven, H., et al., (2019)	Environmental impacts	Food waste management
10	Istanbul	Yıldız-Geyhan et al., (2019)	Environmental impacts	Packaging waste management
11	Shanghai	Chen et al., (2020)	Net carbon emissions	Food waste and residual waste
12	Shanghai	Liu et al., (2021)	GHG emissions	MSW Disposal Process Scenarios
13	Beijing	Zhao et. al., (2021)	Energy recovery efficiency, LCC and benefit, GHG emissions	MSW Disposal Process Scenarios
14	Delhi	Mandpe et al., (2022)	Environmental and economic impacts	Current MSWMS

Mendes et al. (2003) applied LCA to evaluate the environmental impacts of disposal methods, including landfilling, composting, and biological treatment, for simply biodegradable fractions of MSW in Sao Paulo City, Brazil. Landfilling, composting, and bio gasification were analysed in terms of global warming, acidification, and nutrient enrichment impact categories. It was determined that landfilling process has the highest environmental impacts in the global warming and nutrient enrichment categories, while the composting process has the highest environmental impact in the acidification potential category. Besides, they stated that the high potential acidification impact caused by the composting process can be decreased by adding gas treatment to the system, and the application of a biofilter for gas treatment markedly decreases the gaseous emissions.

Jha et al. (2008) analysed GHG emissions from in landfill sites of Chennai megacity. They determined that the emission flux in the Chennai ranged from 1 to 23,5 mg CH_4 m^{-2} h^{-1}, 6 to 460 µg N_2O m^{-2} h^{-1} and 39 to 906 mg CO_2 m^{-2} h^{-1} at Kodungaiyur and 0,9 to 433 mg CH_4 m^{-2} h^{-1}, 2,7 to 1200 mg N_2O m^{-2} h^{-1} and 12,3 to 964,4 mg CO_2 m^{-2} h^{-1} at Perungudi. CH_4 emission estimates from municipal solid waste management were found to be about 0,12 Gg in Chennai for the year 2000.

Zhao et al. (2009) evaluated the current and possible patterns of MSW management in Tianjin megacity regarding GHG emissions, using LCA. Six scenarios were evaluated, and it was found that the current MSWM of Tianjin released 467,34 Mg CO_2 eq GHG emissions per year.

Similarly, Bohra et al. (2012) evaluated the GWP of various municipal waste management options in Delhi megacity (India) using LCA. They stated that the scenario of maximum diversion of waste from landfills provides the least impact on global warming.

Angelo et al. (2016) harmonically combined LCA and Multi-criteria decision analysis (MCDA) techniques, using the management of food waste from households in the megacity of Rio de Janeiro as a case study. GWP, ODP, PM 2,5, ionizing radiation, photochemical oxidant formation, freshwater terrestrial and marine eutrophication, acidification, ecotoxicity, abiotic resource depletion, human toxicity cancer, and non-cancer effects impact categories were analysed with the ILCD method.

The LCA method was used by Yıldız-Geyhan et al. (2016) to determine the environmentally best source-separated packaging waste collection system in Istanbul, Türkiye. They showed that the current packaging waste collection system is one of the environmentally most advantageous scenarios. Additionally, they stated that Scenario-5, where waste is separated into mixed packaging waste and glass waste fractions and collected in two different plastic curb-side bins, and Scenario-6, where waste is separated into paper-cardboard, heavy-lightweight packaging waste, and glass waste fractions and collected in three different plastic curbside bins, were found to be other favourable scenarios, respectively.

Saraiva et al. (2017) compared the environmental impacts of three management alternatives for the organic fraction of municipal solid waste in Rio de Janeiro using the LCA methodology. GWP, ODP, PM, photochemical oxidant formation (POF), marine eutrophication, acidification, human cancer and non-cancer toxicity effects impact categorized were analysed with the ILCD (2011) method.

An emergy LCA analysis of MSWM study for Beijing was conducted by Liu et al. (2017). Emergy is defined as all the utilized energy (exergy) directly and indirectly expended in the creation of a product or service. This is expressed as solar equivalent joule (sej). Four MSW collection and treatment strategies were analysed, and results indicated that the total emergy use is $9{,}08 \times 10^{13}$ sej/t-waste for the incineration process, $6{,}59 \times 10^{13}$ sej/t-waste for sanitary landfills, $5{,}48 \times 10^{13}$ sej/t-waste for composting and $4{,}93 \times 10^{13}$ sej/t-waste for collection and transportation process without considering economic and ecological losses. Considering the emission impact, the total emergy use was determined as $1{,}15 \times 10^{14}$ sej/t-waste, $1{,}05 \times 10^{14}$ sej/t-waste, $9{,}90 \times 10^{13}$ sej/t-waste, and $5{,}03 \times 10^{13}$ sej/t-waste for incineration, sanitary landfills, composting, and collection and transportation process, respectively. They also stated increasing the source separation rate would make recycling more favourable and that source separation prevents ecological and economic losses.

Guven et al. (2019) evaluated future food waste management alternatives in Istanbul using LCA. They found that the current waste management has the worst environmental performance compared to proposed waste management scenarios, which include anaerobic digestion, thermal treatment, and co-treatment with municipal wastewater. The thermal treatment scenario has been found to have the best environmental performance in most of the impact categories, including climate change.

Yıldız-Geyhan et al. (2019) analysed existing and alternative municipal packaging waste management systems in the Maltepe district of Istanbul in terms of environmental and social impacts with LCA. They found that informal collection systems are environmentally more effective than formal collection systems due to the amount of recycled material, and informal collection systems have socially negative effects. They stated that the integration of waste collectors into the formal collection system will increase the efficiency of the recycling system and decrease the negative effects of the informal collection system.

Chen et al. (2020) applied the LCA methodology and Life Cycle Inventory (LCI) to determine net carbon emissions during the treatment of food waste and residual waste collected from 2.365 families in three pilot communities in the Putuo district of Shanghai, China. This study was implemented at the pilot scale, not the national scale.

Liu et al. (2021) examined the variations in GHG emission patterns from waste disposal processes in the megacity of Shanghai from 2005 to 2015. They combined the method recommended by IPCC and the bottom-up method for the detailed GHG emission estimations and determined that landfill contributes to 81,88% of total GHG emissions. Meanwhile, the GHG emissions from incineration plants increased from $1{,}8\times10^8$ to $3{,}8\times10^8$ kg CO_2 eq from 2005 to 2015, with the amount of incinerated MSW increasing from $1{,}02\times10^9$ to $2{,}50\times10^9$ kg. They also found that the GHG emission intensity of incineration is lower than that of landfill and composting, and the GHG emission intensity could influence both the scale and the operation conditions of the waste disposal facilities. Furthermore, GHG emissions could be reduced by around 54,07% with the implementation of waste source sorting and an incineration-dominated in disposal process.

In the other study conducted in Beijing, energy recovery efficiency, life cycle cost (LCC), and benefits, as well as GHG emissions, were analysed using LCA by Zhao et al. (2021). They developed four different scenarios, each involving the application of different technologies, and found that Scenario 4 (MBT system + RDF system) has the highest energy recovery efficiency and the highest GHG emissions reduction potential.

Mandpe et al. (2022) analysed the environmental and economic impacts of only the current waste management system in Delhi city using the Gabi 17.00 software for LCA. For this scope, landfilling, composting, anaerobic digestion, and recycling methods were analysed in terms of GWP, eutrophication potential (EP), acidification potential, abiotic resource depletion potential, and photochemical oxidation (PO) potential parameters using CML 2001 Life Cycle Impact Assessment (LCIA) method.

As seen from the LCA publications listed above, only sub-sections of waste management, such as biowaste, packaging waste, and food waste, have been studied on MSWM in the megacities. Out of these publications, 5 studies are conducted on current and alternative MSWMS, but only GWP, GHG, and energy production are analysed in these studies.

2.4.4 Input-Output Studies on Municipal Solid Waste Management in the Megacities

Based on searches conducted in Science Direct and WOS databases, the keywords "Input-Output Analysis" are searched with "MSWM" for both "Megacities" and "Istanbul" separately. Only three studies are found from the Science Direct database related to this search, and they are shown in Table 6. Two of these studies, conducted by Juárez-Hernández (2021) and López de Munain et al. (2021), evaluated input-output balances of waste flows in terms of mass. On the other hand, the remaining study performed by Mandpe et al. (2022) evaluated input and output balances of the current waste management of Delhi in terms of both mass and energy. This study is also listed as one of the found LCA publications on MSWM in megacities, indicated by the number 14 in Table 5.

Table 6. Input-Output Analysis Publications on MSWM in the Megacities (Science Direct, 2022)

	Megacities	References	Parameters	Waste Type/Process
1	Mexico City	Juárez-Hernández, S., (2021)	Waste Flow Analysis in Mass	Current MSWMS and alternative scenarios
2	Buenos Aires	López de Munain, D., et. al., (2021)	Waste Flow Analysis in Mass	Current MSWMS
3	Delhi	Mandpe A., et al., (2022)	Waste Flow Analysis in Mass and Energy	Current MSWMS

Juárez-Hernández (2021) modelled waste flows of Mexico City, including the input and output of the current MSWMS and alternative strategies, in terms of mass balance. Additionally, the current and alternative MSWM strategies of Mexico City were analysed in terms of fossil energy use, GHG emission, resource recovery, and economic cost in this study.

López de Munain, et al. (2021) characterized waste flows and processes, which are the constituent parts of MSWM, using with material flow analysis (MFA) tools. The results show that 46% of the waste was disposed of in landfills, while 54% of the waste was recycled or reused in different activities.

Mandpe et al. (2022) performed an input-output analysis of the current MSWMS of Delhi. This study is the same as one of the found LCA publications on MSWM in the megacities mentioned in Chapter 2.1.1. They analysed the environmental and economic impacts of the current MSWMS for the Delhi megacity using the LCA tool, and they also analysed the input and output flows of the current MSWMS, including transfer stations, composting, and landfill processes in the inventory analysis.

It is seen that although there are many studies performed on waste management. SWM, and MSWM in megacities. However, only 14 studies evaluated the MSWM in megacities, including Istanbul, using the LCA tool (Table 5) and 3 studies evaluated input-output analysis of MSWMS in megacities (Table 6).

Based on LCA studies performed on MSWM in megacities, 7 out of these studies considered a single waste type, such as biodegradable, food, and packaging waste. Only current waste management situation and only landfill process were considered in 2 out of them. In contrast, the remaining 5 studies analysed current and alternative MSWM strategies of a megacity, but the strategies were only analysed in terms of GHG emissions. GWP was analysed in 3 out of these studies, and the strategies were analysed in terms of energy efficiency, LCC, and GWP by Zhao et al. (2021), while the other study performed by Liu et al. (2017) only considered total emergy use.

Based on input-output analysis studies performed on MSWM in megacities, input and output balances of waste flows were evaluated in mass in two out of the three studies conducted by Juárez-Hernández (2021) and López de Munain et al. (2021). The input and output balances of only the current waste management of Delhi were evaluated in terms of both mass and energy in the remaining study performed by Mandpe et al. (2022).

It is evident from the publications mentioned above that there are no studies conducted in the megacities of the world in which input-output analysis has been made by calculating the mass and energy balances and avoided product calculations of the current MSWM system and alternative strategies of a megacity in detail. Additionally, the current MSWM and the different MSWM strategies are analysed using LCA in terms of climate change, ecosystem quality, and human health for the first time. This study is the first comprehensive study in the literature that evaluates input-output analysis of MSWM in terms of both mass and energy, calculates GHG and avoided energy values, and analyses the current MSWM and different MSWM strategies in terms of climate change, ecosystem quality, and human health using LCA in Istanbul and other megacities.

2.4.5. LCA Publications on Municipal Solid Waste Management in Türkiye

According to the literature reviews, the first two publications on waste management options in Türkiye were published in Ankara and Eskisehir cities in 2006 and 2009, respectively.

In the first publication, Ozeler et al. (2006) developed and compared different solid waste management system scenarios for the MSWMS of Ankara using the LCA methodology. The solid waste management methods considered in the scenarios included the collection and transportation of wastes, source reduction, material recovery facility (MRF)/transfer stations (TS), incineration, anaerobic digestion, and landfilling. The study aimed to determine the most environmentally friendly option for the MSWM system in Ankara.

In the second publication, Banar et al. (2009) used the LCA methodology to determine the optimum MSW management strategy for Eskisehir City. Five different scenarios were developed as alternatives to the current waste management system, considering the collection and transportation of waste, MRF, recycling, composting, incineration, and landfilling processes. It was stated that composting was the most environmentally friendly scenario among the created scenarios.

Other publications are related to the evaluation of waste management in small cities such as Sakarya, Aksaray, and Aydın. In the publications by Yay and Erses (2015), LCA methodology was used to evaluate the environmental aspects of a less impactful MSWMS in Sakarya. The functional unit of the study was selected as one ton of MSW generated in Sakarya. The system boundaries included the collection and transportation of MSW and its treatment and disposal by MRF, incineration, composting, and landfilling methods. Data on the process was gathered from a field study conducted in Sakarya and from SimaPro 8.0.2 literature and libraries. The data were evaluated using the CML-IA methodology, employing abiotic depletion, abiotic depletion (fossil fuels), acidification, global warming, ozone depletion, human toxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, and photochemical oxidation. According to their study results, landfilling and incineration were confirmed as the worst waste final disposal alternatives, while composting and material recovery showed better performance.

In the publication by Cetinkaya et al. (2018), the LCA method was used to determine the best MSWM strategy for Aksaray City, Türkiye. Four different scenarios were developed as alternatives to the existing waste management system and evaluated for the best environmental solution. The scenario with 75% landfilling and 25% composting provided the best results in terms of human health and environmental impact.

Yilmazi et al. (2019) aimed to determine an alternative method to decrease the environmental effect of landfill gas and leachate arising from the landfill process in Antalya city, Türkiye. They used SimaPro 7.1 version of LCA software and found that source separation with high public participation and biodegradable waste management are the main important points that will increase waste management efficiency and minimize the environmental impacts.

Ozer and Yay (2021) implemented LCA to determine the most environmentally friendly waste management system of Kirklareli, Türkiye, using SimaPro 9.0.0.49. They analysed impact categories of abiotic depletion (fossil fuels), global warming, ozone layer depletion, human toxicity, freshwater, marine, and terrestrial ecotoxicities, photochemical oxidation, acidification, and eutrophication with the CLM-IA method. They stated that energy recovery reduces the environmental impacts, and the best waste management option for Kirklareli includes material separation for recycling, biomethanisation, and landfilling.

Except for these, there are three LCA publications performed on MSWM in Istanbul megacity by Yıldız-Geyhan et al. (2016), Guven et al. (2019), and Yıldız-Geyhan et al, (2019), but these studies are described in Chapter 2.4.3.

Based on the information provided, it appears that there is a notable gap in detailed LCA and input-output analysis studies on MSWM in Istanbul megacity, Türkiye. This thesis being conducted is the first comprehensive attempt to fill this gap by analysing the current and different MSWM strategies in terms of climate change, ecosystem quality, and human health using both LCA and input-output analysis, considering both mass and energy balances.

3. LITERATURE REVIEW ON MSWM AND LCA

3.1. Solid Waste Definition and Types

Resource Conservation and Recovery Act (RCRA) define "solid waste" as any garbage or refuse, sludge from a wastewater treatment plant, water supply treatment plant, and air pollution control facility, resulting from industrial, commercial, mining, and agricultural operations, and from community activities. It is also determined that the solid waste definition is not restricted to wastes that are physically solid, the definition also includes liquid, semi-solid, or contained gaseous material (USEPA, 2021).

Wastes can be classified according to various factors such as consumption, production, chemical, and physical properties. The wastes generally can be classified as solid, liquid, and gas wastes. Solid wastes are divided into eight sub-sections based on their origin, according to Gunduzalp et al. (2016):

- Household Waste
- Industrial Waste
- Hazardous Waste
- Special Waste
- Medical Waste
- Agricultural Waste
- Park and Garden Waste
- Construction and excavation waste

Household wastes are solid wastes coming from places such as residential, industrial, workplace, and picnic areas that are not covered by hazardous and harmful waste. In Waste Management General Principles Regulation, hazardous wastes are divided into 15 classes according to their hazard characteristics: explosive, oxidizing, highly flammable, irritant, harmful, toxic, carcinogenic, corrosive, infectious, reproductive, mutagenic, substances or preparations that release toxic or very toxic gases by contact with air, water, or an acid. Substances and preparations occurring during the disposal of wastes having any of these properties are ecotoxic wastes. Medical waste includes infectious waste, pathological waste, and cutter-piercing waste. Construction wastes are resulting from the construction of residential, buildings, bridges, roads, and similar infrastructures and superstructures and excavation Wastes are the soil formed because of excavation and similar activities during the preparation of the land before construction (MOEU, 2017).

3.2. Municipal Solid Waste

According to the Directive of the European Parliament and of the Council amending Directive 2008/98/EC on waste; "Municipal waste" means mixed waste and separately collected waste from households including Paper and cardboard, glass metals, plastics, bio-waste, wood, textiles, waste electrical and electronic equipment, waste batteries and accumulators; Bulky waste, including white goods, mattresses, furniture; garden waste, including leaves, grass clipping mixed waste and separately collected waste from other sources that are comparable to household waste in nature, composition and quantity, market cleansing waste and waste from street cleaning services, including street sweepings, the content of litter containers, waste from the park and garden maintenance. Municipal waste does not include waste from sewage networks and treatment, including sewage sludge and construction and demolition waste. "Bio-waste" means biodegradable garden and park waste, food and kitchen waste from households, restaurants, caterers, and retail premises, comparable waste from food processing plants, and other waste with similar biodegradability properties that are comparable in nature, composition, and quantity (EC, 2015).

3.2.1. Source and Composition of Municipal Solid Waste

The contents of solid waste vary depending on the socioeconomic and geographical position of the environment in which it is produced, seasonal conditions, and the methods of collection and storage of waste, as well as the sampling, and classification methods used (Khan et al., 2016).

The first step in solving problems arising from solid wastes is to determine in detail the characteristics of the wastes. It is important to know the proportion of the various groups of substances contained in the solid wastes to select appropriate techniques for accumulation, collection, transportation, evaluation, and disposal. Various factors that change the composition and the amount of solid waste are as follows (Adhikari et al., 2014):

- Seasons
- Horticulture preferences of the region
- Geographical features of the region

- Rainfall
- Economic level of people living in the region
- The region’s preferences for consumption
- Cultural structure

3.2.2. Collection and Transportation of Municipal Solid Waste (MSW)

Waste collection and transport costs can account for up to 70% of the total waste management system cost (Boskovic et al., 2016), which is why achieving a higher recycling rate is crucial. A higher recycling rate decreases collection, transport, and disposal costs by avoiding the high cost of incineration (Larsen et al., 2010). The success of an integrated solid waste management system is directly proportional to the success of the collection system. Achieving the goal of the solid waste management system depends on the intensive, continuous, and timely collection of waste from waste sources. According to the legislation in force in Türkiye, the district municipalities are responsible for the collection of solid wastes in metropolitan cities. The collection of solid waste is an important component of the budget of the district municipalities. Efficient and economical collection of solid waste is essential to reduce the costs that affect the local government. The first condition for the economic recovery of solid waste is a separate collection (Eisted et al., 2009).

The amount of recycling is the most important parameter showing the efficiency of the integrated solid waste system. First, the targets must be specified in the recovery program. The objectives of recovery aim to resource protection, environmental protection, energy recovery, and space-saving. Transfer stations play an important role in the case of long distances and long transport times in solid waste management and making solid waste transport efficient and effective. Transfer stations serve as a step between the collection of solid waste and the transfer of waste to disposal facilities. Domestic and industrial solid wastes brought to the stations by collection vehicles are transported to disposal facilities by loading on larger volume vehicles. One of the most important reasons for the need for transfer stations is to reduce the cost of transporting wastes to disposal facilities. Incineration which is a worldwide thermal technology, biological systems such as composting, biomethanisation, and landfill systems are widely used around the world (Eisted et. al., 2009).

3.3. Municipal Solid Waste Management (MSWM)

Rapid urbanization and industrialization together with increased population directly affect the amount of urban/MSW produced (Singh and Sharma, 2002; Minghua et. al., 2009). MSW refers to the waste produced from human and animal activities, industries, commercial and urban activities (Table 7).

Table 7. General Sources of MSW (Peavy et. al., 1987)

Source	Activities, typical amenities, or locations where wastes are generated	Types of solid waste
Residential	Single-family and multi-family houses, apartments, etc.	Food wastes, rubbish, paper waste, ashes, special wastes
Commercial and institutional	Warehouses, restaurants, markets, office buildings, hotels, shopping malls, schools, print shops, auto repair shops, medical facilities and institutions, prisons, etc.	Food wastes, rubbish, ashes, demolition and construction wastes, special wastes, occasionally hazardous wastes
Open areas	Streets, alleys, parks, vacant lots, playgrounds, beaches, highways, recreational areas, marriage halls, etc.	Street sweepings, roadside litter, rubbish, and other special wastes
Treatment plant sites	Water, sewage, and industrial wastewater treatment processes	Treatment plant sludges

3.4. Integrated Solid Waste Management (ISWM)

3.4.1 General aspects

In the past, MSWM consisted of the collecting, landfill and incineration of domestic waste, while industrial waste was ignored (Bagchi, 2004). Recognizing the limitations of resources and discovery of pollution-borne diseases, waste management has gained importance with advancing technology and increased environmental awareness. Integrated solid waste management (ISWM) has emerged as a product of this development. ISWM can be defined as an appropriate technique, technology, and management plan selected for a specific waste management plan if all economic and social requirements are met (Tchobanoglous et. al., 1993). The order of importance of the recommended methods in the waste management hierarchy is decreasing to the top from the bottom. The characteristics of ISWM can be listed as follows (Ozturk, 2010):

- **Integrity:** Includes all solid waste materials and production resources
- **Creating economic value:** Providing economic value from the solid waste system

- **Flexibility:** Compliance with changes in environmental, spatial, and waste characteristics
- **Based on regional planning:** ISWM should be planned locally due to the productivity that is developing in the right direction

ISWM is a comprehensive waste prevention, recycling, composting, and disposal program. An effective ISWM system considers how to prevent, recycle, and manage solid waste in ways that most effectively protect human health and the environment. ISWM involves evaluating local needs and conditions and then selecting and combining the most appropriate waste management activities for those conditions. The major ISWM activities are waste prevention, recycling and composting, and combustion and disposal in properly designed, constructed, and managed landfills. Each of these activities requires careful planning, financing, collection, and transport (USEPA, 2002).

If cities do not have recycling programs, it is important to determine the percentage of recyclable materials in the waste stream and the percentages of these recyclable materials that are marketable. For cities with recycling programs, the amounts of recyclable materials can provide valuable information, allowing for the setting of capture rates at recycling centres. The municipalities are obliged to ensure the collection and proper management of wastes generated by residents and establishments. To achieve this, the number of funds available from municipal budgets for MSW improvements should be increased (Turan et al., 2009).

3.4.2. Source Reduction

Source reduction is defined as the design, manufacture, and use of materials to reduce their quantity or toxicity before they reach the waste stream. Source reduction is also known as waste reduction, waste prevention, waste minimization, and pollution prevention. It reduces the amount of produced materials and the harmful environmental effects associated with producing and disposing of them (USEPA, 1995).

Source reduction strategies have many favourable environmental impacts, including reducing GHG production, saving energy, and conserving resources, in addition to reducing the volume of the waste stream (Heimlich et al., 2007).

3.4.3. Separate Collection

The separate collection also known as source separation means the separation and collection of different waste fractions in separated containers where they are produced (Rousta et al., 2015). The purposes of separate collection are recycling, reuse, or improved waste management. The materials usually diverted from municipal waste streams by source separation include reusable materials (clothes, accessories, containers, and books), organic waste (food and garden waste), recyclable waste (glass, plastic, metal, paper-cardboard), and hazardous and toxic waste (Lardinois and Furedy, 1999).

3.4.4. Recycling

Recycling is the reprocessing of recovered materials back into the supply chain at the end of product life. Recycled material can also be referred “secondary” as opposed to “primary” material that is extracted from the environment (Worrell, E., 2014).

There are main methods that can be used to recover recyclable materials from MSW which are the collection of source-separated recyclable materials, recyclables collection with processing at centralized materials recovery facilities (MRFs), and mixed MSW collection with processing for recovery of the recyclable materials from the waste stream at mixed-waste processing or front-end processing facilities. Recyclable materials can include paper (newspaper, cardboard, mixed paper, etc.), glass, metals (aluminium, iron, bimetal) and plastics (PET, HDPE, PVC, LDPE, PP, PS, etc.), and other products (Tchobanoglous and Kreith, 2002).

Recycling offers significant benefits. Increasing global demands for virgin resources make their extraction more costly in terms of capital requirements and environmental degradation. Recycling postconsumer waste can help reduce these demands. The production of manufactured products from recycled materials often results in a significant saving of energy. Additionally, recycling provides a domestic source of materials, reducing the dependence on foreign supply and the negative impact of imported materials on the country’s trade balance (USEPA, 1977).

3.4.4. Mechanical-Biological Treatment (MBT)

MBT is a series of mechanical and biological processes aimed at reducing waste material and stabilizing it to reduce emissions from final disposal. Typically, mechanical processes separate waste material into fractions to be further processed (composting, anaerobic digestion, incineration, recycling) which may include separation, shredding, and crushing of the material while biological processes include composting and anaerobic digestion (IPCC, 2006). When composting is used as the main biological process in MBT, no biogas is produced, and mixed waste is converted into stabilized waste material through the rotting process for landfill disposal (Cleaner Production, 2023).

3.4.5. Organic Waste Management

According to the EPA, S.A. (Environment Protection Authority, South Australia) (2019), organic wastes are of biological origin and biodegradable waste that do not contain radioactive and hazardous waste. EU landfill directive (1999/31/EC) defines biodegradable wastes as all anaerobic and aerobically degradable wastes, such as food waste, garden waste, paper, and cardboard wastes. The EU waste framework directive (2008/98/EC), defines biowaste as biodegradable garden and park wastes, as well as kitchen and food waste from households, restaurants, cafeterias, and food-producing places. The term biodegradable waste is a broader term that includes not only domestic waste but also industrial waste, forest waste, agricultural waste, fertilizer, sewage sludge, and natural textiles. (JRC 2011). According to European circular economy and waste policies, biowaste is the main important waste stream and accounts for 34% of MSW generated in EU-28 member states. The recycling of biowaste is indispensable to achieve the EU's target recycling rate of 65% of by 2035. Therefore, separate collection of biowaste will be obligatory for all EU member states from the end of 2023, according to the revised Waste Framework Directive in 2018 (EC, 2018b; EEA, 2020).

In their study, Sonesson et al. (2000) conducted an environmental and economic analysis of the biodegradable wastes. In the study, they used ORWARE software for material flow simulation and employed LCA as the methodology. Four different scenarios were created, and the results are listed as follows: there is no single best scenario as a general solution, and the results are valid for the case study in Sweden. Additionally, they indicated that anaerobic digestion is the best alternative for environmental impacts, excluding resource use and photochemical oxidation. Incineration is as effective as anaerobic digestion for global warming, acidification, and eutrophication parameters, while composting shows promise with the low budget and environmental impacts.

According to the research published by WRAP (2008), in the UK, 25 million tons of organic waste are generated, valued for their organic content. A 20% increase in the composted organic waste rate has been observed in the last 5 years. The study also revealed that 1 Mg of organic waste can produce 300 kWh of energy through anaerobic decomposition. Composting 1Mg of garden waste reduces CO_2 emissions by 90 kg to 230 kg. By composting green waste, approximately 500.000 Mg of CO_2 emissions were reduced in the UK in 2007.

In another study by WRAP (2009) on domestic food and beverage waste, they classified wastes as avoidable, possibly avoidable, and inevitable waste. Avoidable waste includes edible items that are discarded before consumption, such as bread and apple slices. Possibly avoidable waste comprises items that may vary in consumption based on individual preferences, like breadcrumbs and potato skins. Inevitable waste consists of items that can not be consumed, such as bones, banana shells, and eggshells.

Composting

Composting is a process for the recycling organic waste, making it an ecologically sound treatment as the organic fraction of waste (generally about 40 to 80% by weight in household waste) returns to the natural cycle. Compared to other treatment methods, composting has only minor negative effects on the environment (Gajalakshmi and Abbasi, 2008).

In Germany, 7,37 million Mg of biowaste are consigned to 868 composting facilities, and 6,48 million Mg to 1,392 digestion plants (including combined digestion and composting facilities). This is applied to produce around 3,96 million Mg of compost and 4,09 million Mg of fermentation substrate for use in various sectors as fertilizers or soil additives (BMU, 2018).

Apart from treating household waste in composting facilities, vegetable waste and other organic waste are composted in decentralized locations on farms, gardening nurseries, or private gardens. However, this decentralized composting cannot substitute for composting in large-scale facilities. That option is only feasible in rural areas (Gajalakshmi and Abbasi, 2008).

Anaerobic Digestion

Anaerobic digestion (AD) is the most preferred process among biological treatment processes, especially due to process-related high energy recovery and limited environmental impacts, particularly considering the greenhouse effect (Mata Alvarez, 2003). In terms of literature, the anaerobic treatment of solid waste has become popular in this regard. This process is a self-sustaining process in nature to achieve both good quality and shorter biogas yields at shorter reaction times. AD can be an interesting method for energy generation and waste disposal (Rao & Singh, 2004). The AD process can be divided into four stages: pre-treatment, waste digestion, gas recovery, and residual treatment (Buvet et. al., 1980; IEA, 2001).

Anaerobic digestible organic carbons have naturally occurring bacteria. Digestion occurs when organic matter decomposes in an anaerobic environment due to naturally occurring bacteria. Various microorganisms use organic fertilizer, sewage sludge, waste food, and other organic materials under anaerobic conditions during digestion. The chemical reactions that occur during anaerobic digestion are called hydrolysis, fermentation, also acidogenesis (the formation of soluble organic compounds and short-chain organic acids), and methanogenesis (the bacterial transformation of organic acids into methane and carbon dioxide) (Metcalf & Eddy, 2003).

Typically, anaerobic reactors or processes for solid waste can be categorized into several types, primarily based on the feeding mode (continuous mode: single stage, two stages, and batch mode) and the moisture content of the substrate ("wet" and "dry" digestion). Furthermore, these anaerobic reactors can be classified based on the digestion process temperature (mesophilic or thermophilic) and the shape of the reactors (Nayono, 2010).

Anaerobic digestion is considered a "wet" process if the total solid concentration of the substrate is less than 15% and a "dry" process if the concentration reaches 20-40% (Lissens et al., 2001). Two feeding modes are generally used in the anaerobic digestion of solid waste: the batch system and the continuous system. In the batch system, digesters are filled once with fresh feedstock with or without the addition of inoculate and sealed for the complete retention time, after which they are opened, and the effluent is removed. In the continuous system, fresh feedstock continuously enters the digester, and an equal amount of digested material is removed (Nayono, 2010).

3.4.6. Landfilling

The deposition of waste is the most common kind of waste elimination all over the world. The forms of waste deposition can vary from wild dumps on the outskirts of towns to orderly technical facilities in hydrogeological suitable locations. The purpose of a controlled landfill is to act as a barrier for pollutants. This involves implementing appropriate technical measures and maintaining controlled operation of the site to ensure that no emissions can penetrate the environment (Ferronato and Toretta, 2019).

Sanitary Landfill

The sanitary landfill is the disposal of waste in a controlled manner. Landfill areas can also be considered regions where wastes are isolated to prevent harm to the environment (Rushbrook and Pugh, 1999).

Solid waste disposal in landfills has been a common practice for decades, mainly due to its simplicity and the lack of accounting for aftercare and environmental costs. However, a study by Eriksson et al. (2005) shows that reducing landfilling in favour of increasing recycling of energy and materials leads to lower environmental impacts, lower consumption of energy resources, and lower economic costs. Landfilling of energy-rich waste should be avoided as much as possible, not only because of the negative environmental impacts but also due to its low recovery of resources.

In Türkiye, landfill sites are divided into three classes according to the waste types accepted in the area. These classes and types of waste are as follows (MOEU, 2016):

- **Class-I:** Hazardous waste
- **Class-II:** Municipal solid waste and non-hazardous waste
- **Class-III:** Inert waste that is not undergoing significant physical, chemical, or biological transformation.

In Europe, the introduction of the European Landfill Directive (EC, 1999) has stimulated European Union member states to develop sustainable solid waste management strategies including collection, pre-treatment, and final treatment methods. According to the directive, member states are obligated to reduce the amount of biodegradable solid waste deposited in sanitary landfills. As a result, by the year 2020, there should be only less than 35% of the total biodegradable solid wastes produced in 1995 being deposited in sanitary landfills. According to EU waste legislation and the policies of the EU member states, landfilling of municipal waste should be gradually limited to 10% by 2030 (EC 2008, Waste Framework Directive).

Uncontrolled Dumping

A simpler alternative to landfilling is the uncontrolled dumping method. This waste disposal method involves the uncontrolled release of waste into the environment without any precaution for leachate, gas emissions, and disease-bearing animals, and microorganisms. It poses a danger to public health (UNEP, 2005).

3.4.7. Incineration

Incineration is a common technique for treating MSW that produces energy in the form of steam for heating and electricity generation. Incineration processes take place between 750^{o}C to 1000^{o}C and can be coupled with steam and electricity generation processes. The incineration process can reduce MSW volume by 80–90%. Electricity production in combination with energy recovery from flue gases in thermal treatment plants is an integral part of MSWM for many industrialized countries (Daura, 2016).

The combustion of solid waste has been used as an efficient way to convert the energy stored in it into useful heat. The energy content (heating value/lower calorific value) of the waste is a crucial parameter, mainly depending on the waste composition. Different types of waste have different calorific values. Wastes with higher calorific values, such as plastics, wood, and textile waste, provide fuel for waste-to-energy plants because of their high heating value, while inert wastes such as construction and demolition wastes, glass, and metals are not suited for incineration. Additionally, MSW in many developing countries has high moisture or ash content (or both), making incineration an inappropriate alternative (Dolgen et al., 2005).

Incineration is a process that generates gaseous pollutants, such as sulphur oxides (SOx), carbon oxides (COx), nitrogen oxides (NOx), polyaromatic hydrocarbons (PAH), and heavy metals. These pollutants are dangerous and require additional treatment in a flue-gas cleaning system (Beyene et al., 2018). In a grate incinerator, the grate moves the waste in the combustion chamber through different zones in a tumbling manner. This tumbling motion ensures that the waste is well-mixed, and uncombusted materials are readily exposed to the heat. Rotary kilns are similar to moving grates in the process, except that the incineration occurs in a rotating chamber. In the rotary kiln, waste is transported by rollers under a cylindrical container that rotates around its axis. There is a fluidized bed of inert where the waste is continuously fed material at the bottom of the combustion chamber. Air flowing under the bed constantly moves the waste to provide more complete combustion (Al Qattan et al., 2018).

3.5. Municipal Solid Waste Management (MSWM) in the EU and Türkiye

3.5.1. Municipal Solid Waste Management in the EU

Figure 2 shows municipal waste generation by country expressed in kilograms per capita, covering the periods from 2005 to 2020. The annual amount of generated MSW in the EU was 505 kg per person in 2020, while this amount was 467 kg per person in 2005. The MSW generation totals vary considerably, and the variations reflect differences in consumption patterns and economic wealth. They also depend on how municipal waste is collected and managed. There are differences between countries regarding the degree to which the wastes from commerce, trade, and administration are collected and managed together with the waste from the households. Denmark had the highest waste generation, with a rate increase of 62,2% in 2020. Waste generation increased to 845 kg person in 2020 from 521 kg per person in 2005 (Eurostat, 2020).

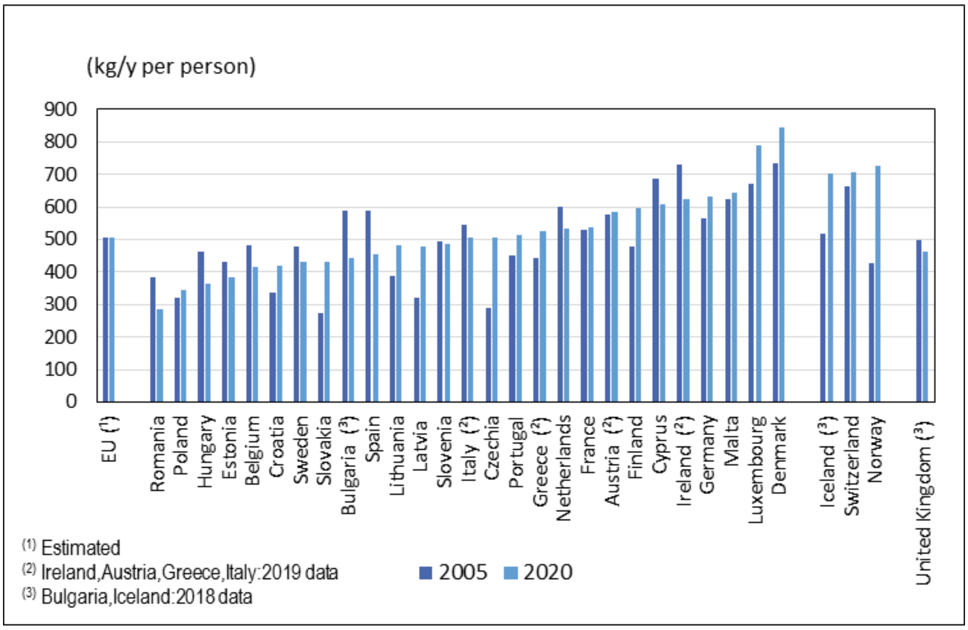

Figure 2. MSW Generation in the EU Member States (Eurostat, 2020)

Figure 3 shows the level of municipal waste treatment methods (landfill, incineration, material recycling, composting, and other) in the EU-28 between 1995 and 2020. The amount of landfilled MSW was 52 million Mg (115 kg/person) in 2020, while this amount of the waste was 121 million Mg (286 kg/person) in 1995.

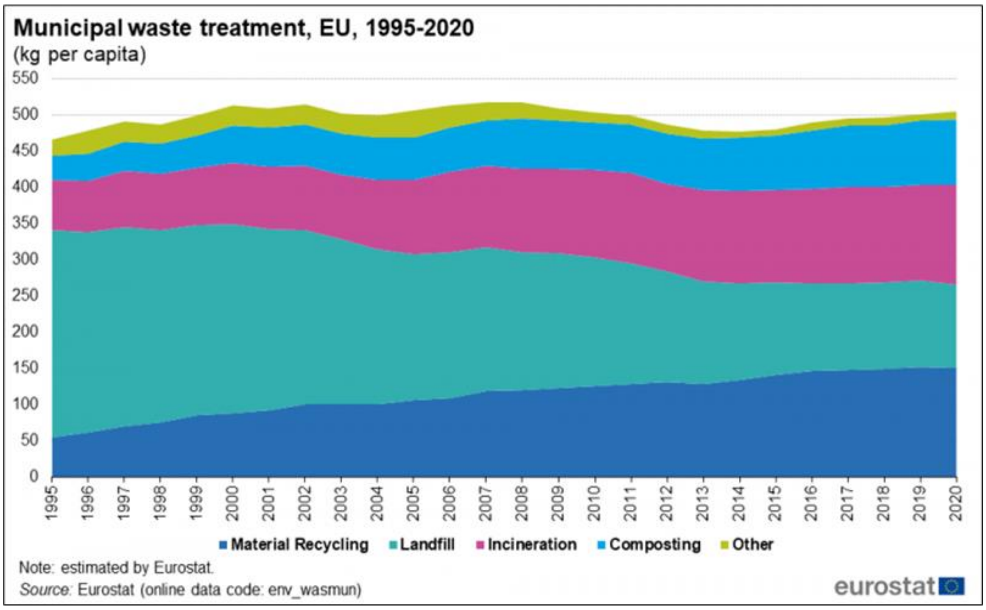

Figure 3. Municipal Waste Treatment in the EU-28 (Eurostat, 2020)

The amount of material recycling increased to 67 million Mg (151 kg per person) in 2020 from 43 million Mg (100 kg per person) in 1995. The overall share of recycled municipal waste increased to 47% from 17%. The amount of composting also increased to 40 million Mg (90 kg per person) in 2020 from 24 million Mg (57 kg per person) in 1995. Waste incineration has also increased steadily in the reference period, with the amount of incinerated MSW in the EU-28 increasing to 61 million Mg (137 kg per person) in 2020, while this amount was 39 million Mg (90 kg per person) in 1995.

3.5.2. European Union (EU) Legislation

The environmental issue, one of the EU's most important agenda items recently, concerns the broader objectives the EU has brought with it and includes about 300 by-laws and directives.

The basic principles of the environment include the integration of environmental protection with all other community policies, the protection of the environment in all EU units, the prevention of damage, the prevention of environmental damage in the first place, and 'polluter pays' principle. The EU's waste management policy is based on the waste management hierarchy and producer responsibility. The EU regulates direct waste management through 14 directives, two of which can only be applied only to member states, and the remaining directives can be applied to the countries participating in the accession process and are necessary to harmonize their legislation before entry. In general, these arrangements represent a mandate for the member states, and these regulations bring serious responsibilities for countries with the status of a candidate country (Goren and Ozdemir, 2010).

The range of EU Directives dealing with waste management includes the Waste Framework Directive 2008/98/EC of the European Parliament and the Council of 19 November 2008 on waste, repealing certain directives. This directive repealed Directive 2006/12/EC of the European Parliament and of the Council of 5 April 2006 on waste (the codified version of Directive 75/442/EEC as amended), Hazardous Waste Directive 91/689/EEC, and the Waste Oils Directive 75/439/EEC (Table 8). It provides a general framework of waste management requirements and sets the basic waste management definitions for the EU.

Circular economy action plan (CEAP) is a crucial part of the European Green Deal, a comprehensive strategy launched by the European Commission in March 2020. The main objective of CEAP is to steer the EU towards achieving climate neutrality by 2050 and halting biodiversity loss. The main topics of CEAP are sustainable product policy framework, key product value chains (electronics and ICT, batteries, and vehicles, packaging, plastic, textiles, construction and buildings, food, water, and nutrients), less waste more value, realizing circularity for people, regions, and cities, crosscutting actions (EC, 2020).

The inclusive targets of this action plan are:

- Shift the focus away from waste disposal and treatment to keep materials and products in productive use for longer, thus preventing the waste of resources and promoting reuse.
- Make manufacturers who produce and sell disposable products for profit environmentally responsible.
- Provide measures that promote sustainable economic models, for example, promoting the use of recycled materials rather than virgin materials.
- Utilize the reach and influence of all sectors, including the voluntary sector, producers/manufacturers, regulatory agencies, and civil society,
- Support clear and steady institutional arrangements for the waste sector, including empowering local authorities' roles (Ireland's National Waste Policy, 2020).

Table 8. EU Waste Legislation

Year (Recent Version)	EU Waste Directive
2020	EU Green Deal and Circular Economy Action Plan (2020/98/EC)
2012	Waste Electrical and Electronic Equipment (WEEE) Directive (2012/19/EC)
2008	Waste Framework Directive (2008/98/EC)
2006	Directive on Waste Batteries and Accumulators (2006/66/EC)
2006	Directive on the Management of Waste from Extractive Industry (Mining Directive) (2006/21/EC)
2000	End of Life Vehicles (ELV) Directive (2000/53/EC)
2000	Directive on Waste Incineration (2000/76/EC)
1999	Directive on the Landfill of Waste (1999/31/EC)
1994	Packaging and Packaging Waste Directive (94/62/EC)
1991	Directive on Batteries and Accumulators (91/157/EEC, as amended)
1975	Directive on Waste (75/442/EEC)

The Ellen MacArthur Foundation defines a circular economy as one that is restorative and aims to maintain the utility of products, components, and materials, retaining their value (EMF, 2015a). This approach minimizes the need for new inputs of materials and energy while reducing environmental pressures linked to resource extraction, emissions, and waste. The European Union's approach to waste management is based on the "waste hierarchy" which sets the following priority order when shaping waste policy and managing waste at the operational level: prevention, (preparing for) reuse, recycling, recovery, and as the least preferred option, disposal (which includes incineration and landfilling without energy recovery).

Waste Framework Directive 2008/98/EC sets the basic concepts and definitions related to waste management, such as definitions of waste, recycling, and recovery. It explains when waste ceases to be waste and becomes a secondary raw material (so-called end-of-waste criteria), and how to distinguish between waste and by-products. The directive lays down some basic waste management principles: it requires that waste should be managed without endangering human health and harming the environment, and without risking water, air, soil, plants or animals, causing a nuisance through noise or odours, and adversely affecting the countryside or places of special interest (EC, 2008).

Waste legislation and policy of the EU member states shall apply as a priority order the following waste management hierarchy (Fig.4).

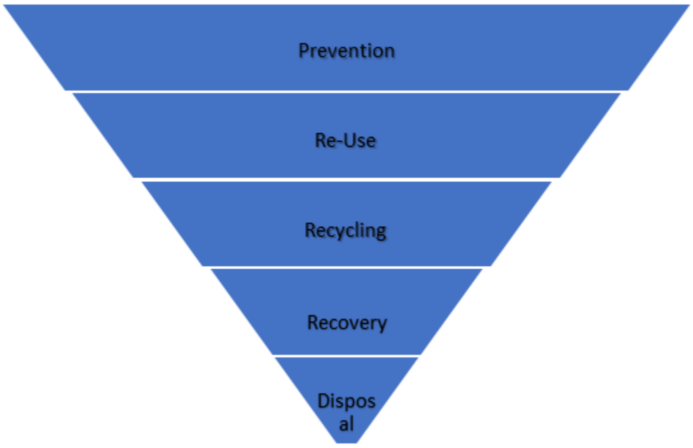

Figure 4. EU Waste Hierarchy (EC, 2008)

The main elements of the proposals to amend EU waste legislation are:

- Increase the target for preparing re-use and recycling of municipal waste to 65% by 2030
- Increase the targets for preparing for reuse and recycling for packaging waste and simplify the set of targets
- Gradually limit the landfilling of municipal waste to 10% by 2030
- Harmonize and simplify the legal framework for by-products and end-of-waste status
- Implement new measures to promote prevention, including addressing food waste, and re-use
- Introduce minimum operating conditions for extended producer responsibility

3.5.3. Municipal Solid Waste Management (MSWM) in Türkiye

As in many emerging countries, solid waste generation is an important environmental problem in Türkiye. The most common method of waste disposal in the country, especially for municipal waste, is landfilling. The MSW is collected on a regularly scheduled basis. The metropolitan municipality and other municipalities are responsible for providing the collection, transportation, separation, recycling, disposal, and storage of waste services.

Table 9 illustrates the total number of municipalities, the number of municipalities which provided waste services, the amount of collected waste, the average collected waste, and the disposal/recovery methods between 2004 and 2020. The number of municipalities providing waste service was 1.387 out of a total of 1.389 municipalities in 2020, while the number was 2.921 out of a total of 3.227 municipalities in 2001. The landfilling rate increased to 69,43% in 2020, from 33% in 2001, while dumping and open burning rates decreased to 17% and 0,058% in 2020, from 58% and 1,4% in 2001, respectively. The results of the survey also demonstrate that the collected average daily MSW production was 1,16 kg/capita in 2018 and 1,13 kg/capita in 2020, respectively. The highest values were 1,35 kg on average between 2001 and 2004.

Table 9. Municipal Solid Waste (MSW) Data of Türkiye (TURKSTAT, 2021)

	2004	**2006**	**2008**	**2010**	**2012**	**2014**	**2016**	**2018**	**2020**
Total Number of Municipality	3.225	3.225	3.225	2.950	2.950	1.396	1.397	1.399	1.389
Number of Municipality Providing Waste Services	3.028	3.115	3.129	2.879	2.894	1.391	1.390	1.395	1.387
Amount of collected MSW (Thousand Mg)	25.014	25.280	24.361	25.277	25.845	28.011	31.584	32.209	32.324
Average MSW production per person (kg/d)	1,31	1,21	1,15	1,14	1,12	1,08	1,17	1,16	1,13
Disposal/Recovery Methods	**Percentage of Waste (%)**								
Dumping	65,6	59,1	52	43,5	37,8	35,5	28,8	20,2	17
Open Burning	0,4	0,9	1	0,5	0,4	0,01	0,032	0,02	0,058
Landfill	28	37,3	45	54,4	59,9	63,6	61,2	67,2	69,43
Compost	1,4	1	1,1	0,8	0,6	0,4	0,51	0,38	0,36
Lake and River Disposal	0,6	0,3	0,2	0,2	0,1	0,06	0,002	0,002	0,002
Burial	1,7	0,6	0,4	0,1	0,4	0,02	0,026	0,006	0,02
Other Recovery Facilities	-	-	-	-	-	-	9,3	11,9	12,83
Other Disposal Processes	2,3	0,8	0,3	0,5	0,8	0,41	0,13	0,292	0,30

In 2020, a total of 32,32 million Mg of waste was collected in municipalities of Türkiye. Out of this waste, 69,43% was sent to landfill facilities, 0,36% was sent to the composting process, 17% was disposed of in dumping sites, and 12,83% of the recyclable part was sent to recovery facilities. Additionally, 0,08% of the waste was improperly disposed of through burning, burying, or dumping into the streams or fields (Figure 5).

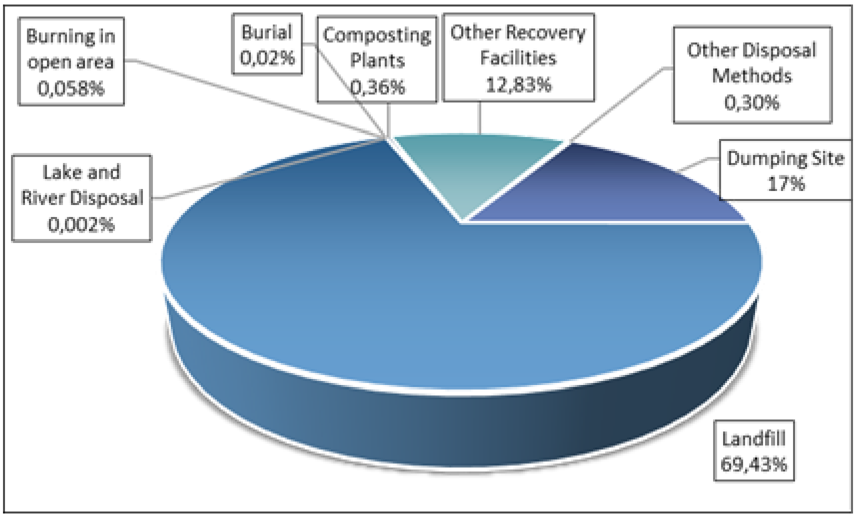

Figure 5. MSW Disposal Methods in Türkiye (TURKSTAT, 2021)

3.5.4. Legislation in Türkiye

Although many different units deal with solid waste management in Türkiye, there is no integration or interaction between them. There are many environmental laws and regulations in the country related to waste management and the use of appropriate technology. The first of these is the "Environmental Law" published in 1983. The purpose of this law is to protect the environment, which is the common asset of all living things, in line with the principles of a sustainable environment and sustainable development.

All the regulations related to waste management implemented in Türkiye are presented in Table 10.

The Hazardous Waste Control Regulation, which was published in the Official Gazette on 14.03.2005 with the number 25755, was repealed one year after the Waste Management Regulation came into force on 02 April 2006. The general framework and obligations related to waste management, especially hazardous wastes, are included in the Waste Management Regulation (MOEU, 2021).

Table 10. Waste-Related Regulations in Türkiye (MOEU, 2021)

First Version	Recent Version	Regulation of Waste in Türkiye
-	2019	Regulation on Zero Waste (Official Gazette Nr: 30829)
2008	2019	Regulation on Control of Waste Oils (Official Gazette Nr: 26952)
2010	2017	Regulation on Waste Incineration (Official Gazette Nr: 30031)
2004	2017	Regulation on the Control of Packaging and Packaging Waste (Official Gazette Nr: 30283)
1993	2017	Regulation for Control of Medical Waste (Official Gazette Nr: 29959)
2011	2015	Regulation of Mining Waste (Official Gazette No: 29417)
2005	2015	Regulation on Control of Herbal Oils (Official Gazette Nr: 29378)
1991	2015	Regulation on the Waste Management (Official Gazette Nr: 29314)
2001	2012	Regulation on the Waste Electrical and Electronic Equipment (Official Gazette Nr: 28300)
2006	2010	Regulation on the Landfill of Waste (Official Gazette Nr: 27533)
2003	2009	Regulation on End-of-Life Vehicles (ELV) (Official Gazette Nr: 27448)
2003	2007	Regulation on the Control of PCB or PCT (Official Gazette Nr: 26379)
1994	2007	Regulation on the Control of End-of-Life Tires (Official Gazette Nr: 26357)
1995	2005	Regulation on Control of Hazardous Waste (Official Gazette Nr: 25755)
2001	2004	Regulation on the XContrXol of Used Batteries and Accumulators (Official Gazette Nr: 25569)
-	2004	Regulation on Excavation Soil, Construction Waste and Debris (Official Gazette Nr: 25406)

3.6. Life Cycle Assessment (LCA)

3.6.1. Life Cycle Assessment (LCA) Definition

LCA is a measurement tool used to evaluate the environmental performance of products throughout their life cycle, where "raw materials" (the place where raw materials are extracted) to "grave" (the place where the product is eventually laid) (Schenck, 2005).

LCA is defined as a technique for assessing the environmental impacts and potential effects of a product by compiling an inventory of inputs and outputs within a product system. This assessment helps to identify the potential environmental impacts associated with these inputs and outputs (Fig.6). The results of the inventory analysis and impact assessment are then interpreted in relation to the study’s objectives (Liamsanguan and Gheewala, 2008).

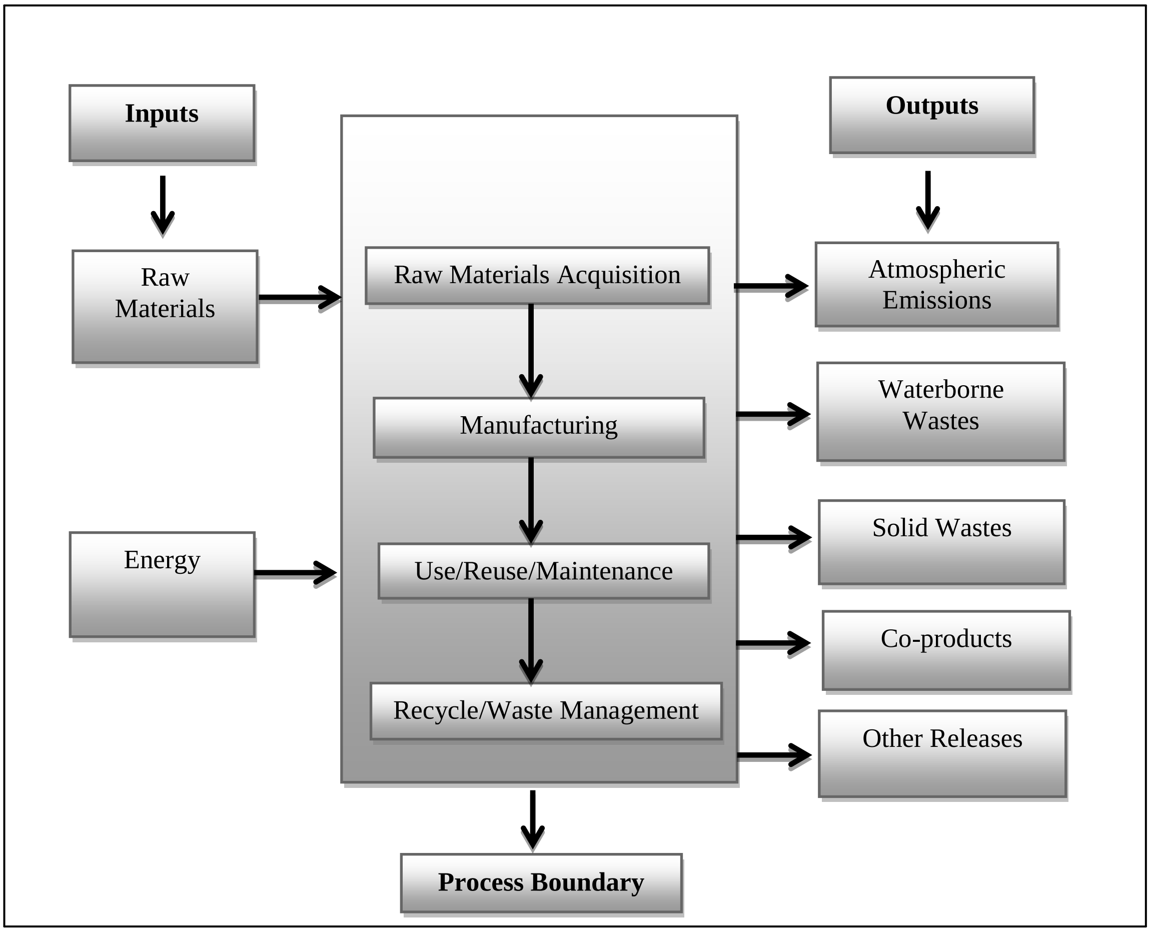

Figure 6. LCA Process (ISO 14040, 1997)

In the idea of the life cycle, a cradle of action is implied, and it can help to

- Separate environmental emissions for air, water, and soil for each life cycle stage.
- Identify the stages and the processes that contribute significantly to environmental impacts.
- Systematically evaluate environmental results for a given product or process.
- Analyse and compare environmental changes between various products or processes.
- Identifying shifts in environmental impacts between environmental media and life cycle stages.
- Evaluate the environmental impacts of the material consumption at various geographical levels.
- Define the effects of a given product or process throughout its entire life cycle or at specific stages.
- Understand the relative environmental burdens resulting from changes in products or processes over time.

- Compare the environmental effects of alternative processes or products.
- Determine the effects of product substitution.
- Provide information on the trade-offs between alternative processes, products, and materials.

3.6.2. Life Cycle Assessment (LCA) Components

There are four linked components of LCA (Fig. 7):

- **Goal and scope definition:** This involves identifying the purpose of LCA, the expected outcomes, and setting the study's boundaries (what is included and excluded) and assumptions based on the defined goals.
- **Life-cycle inventory:** Quantifying the energy and raw material inputs and environmental releases associated with each stage of production.
- **Impact assessment:** This stage assesses the impacts on human health and the environment linked to the energy and raw material inputs and environmental releases quantified during the inventory phase.
- **Interpretation:** In this stage, opportunities to reduce energy consumption, material inputs, or environmental impacts at each stage of the product's life cycle are evaluated (ISO 14040, 1997).

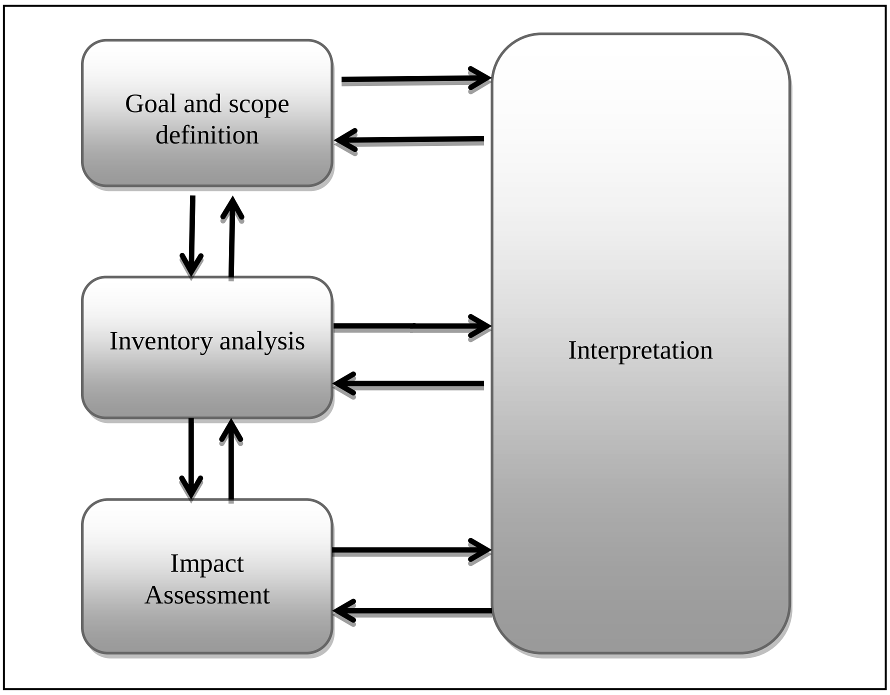

Figure 7. Life Cycle Assessment (LCA) Components (ISO 14040/44)

a) Goal and Scope Definition

The goal of the study is unambiguously states (ISO 14044, 2006):

- The intended application
- Reasons for carrying out the study
- Intended audience (who will the LCA be communicated to ?)

While the goal definition determines the level of sophistication of the study and requirements for reporting, the definition of the scope of an LCA sets the borders of the assessment, i.e., what may be included in the system and what detailed assessment methods are to be used. In defining the scope of an LCA study, the following elements must be considered and clearly described (Kulkarni et. al., 2009):

- The functions of the system, or in the case of comparative studies, systems
- The functional unit
- The system to be studied
- The system boundaries
- The allocation procedures
- The types of impact, the methodology of impact assessment, and subsequent interpretation to be used
- Data requirements
- Assumptions
- Limitations
- The initial data quality requirements
- The type of critical review if any
- The type and format of the report required for the study.

b) Inventory Analysis

At this stage, energy, water, raw material uses and environmental emissions resulting from these factors are determined. Life cycle inventory (LCI) is a process that calculates raw material and energy needs, atmospheric and waterborne emissions, solid wastes, and other releases of a product, process, or activity for the entire life cycle. In the life cycle inventory phase, all relevant data are collected and classified. The comparative environmental impacts or potential changes in these can’t be determined without LCI analysis.

Details and the level of accuracy of the collected data directly affect the accuracy of the other stages of the LCA study and the usability of results. LCI analyses can be used in various forms. An example is the comparison of products or processes and the consideration of environmental factors in the selection of materials. Additionally, inventory analyses can assist governments to set policies and develop legislation (Demirer, 2011a).

The LCI has four phases:

- Establishment of the process flow diagram being evaluated
- Development of a data collection plan
- Collection of data
- Evaluation and reporting

c) Impact Assessment

The IMPACT 2002+ (Impact Assessment of Chemical Toxics) method was originally developed by the Swiss Federal Institute of Technology. The method is used to link 14 impact categories to 4 damage categories. Fig. 8 gives in detail the impact and damage categories used in the IMPACT 2002+ method and their relationships. New concepts and methods have been developed to evaluate and compare human toxicity and ecotoxicity data for IMPACT 2002+ (Jolliet et al., 2003).

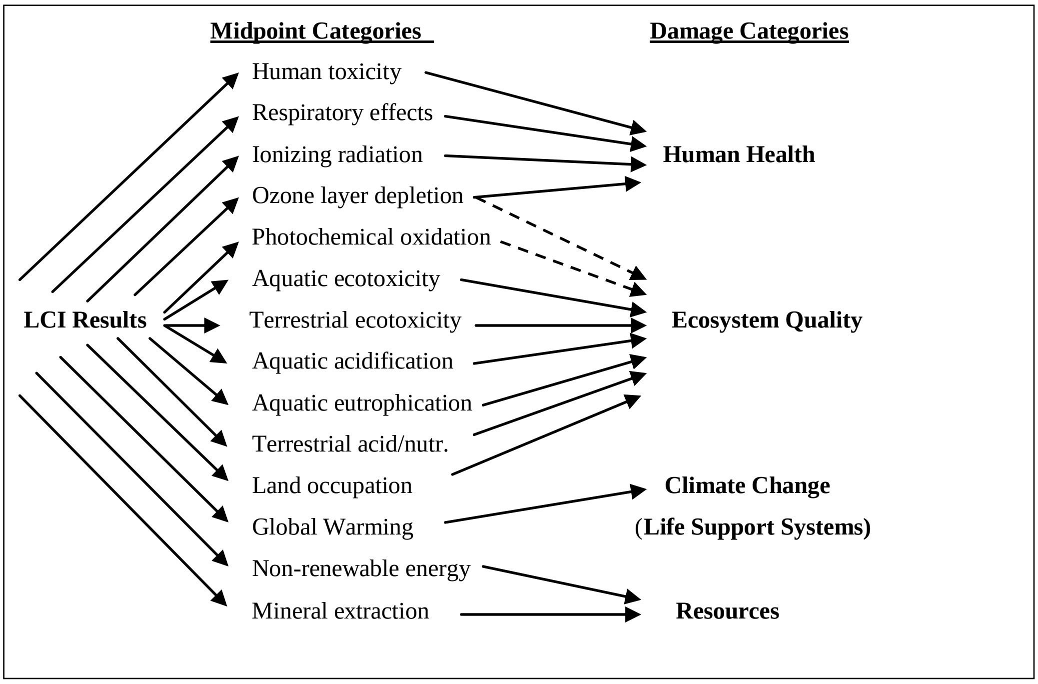

Figure 8. IMPACT 2002+ Categories (ISO 14040, 1997)

Impact Assessment involves category definition, classification, characterization, and valuation/weighting stages. Although category definition, classification, and characterization stages are obligatory for impact assessment, the normalization/valuation/weighting stage is dependent on the goal and scope of the LCA study:

- **Category Definition:** This is the first stage of impact assessment and impact categories category indicators and characterization models are selected in this stage. This phase should be completed as part of the purpose and scope description, to guide the data collection process at the LCA phase.
- **Classification**: The classification stage aims to categorize the inventory results and link them with the relevant impact categories (Fig. 9).
- **Characterizat0ion:** Life Cycle Impact Assessment (LCIA) results are converted to indicators representing human health and environmental impacts. This is achieved using characterization factors, also known as equivalence factors, which are summed to provide an overall impact category total.
- **Normalization/valuation/weighting:** This stage isn't obligatory for the impact assessment phase and is dependent on the goal of the LCA study.

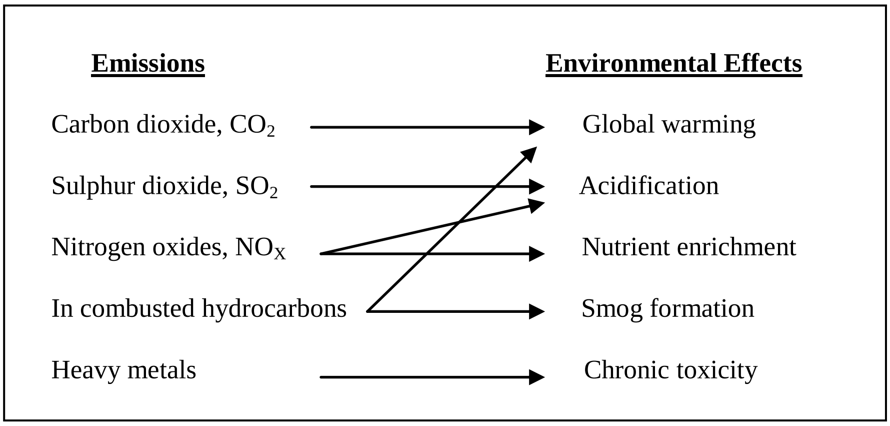

Figure 9. Classification of Emissions (ISO 14044, 2006)

d) Interpretation

Interpretation is the fourth phase in the LCA containing the following main issues (ISO, 1997):

- Identification of significant environmental issues
- Evaluation

- Conclusions and recommendations

The different elements are explained in relation to the ISO standard. The ISO standard on interpretation is the least developed part of the standard and therefore the description below is expected to be revised when the standard is finally approved.

Life cycle assessment interpretation is a systematic procedure to identify, qualify, check, and evaluate information from the conclusions of the inventory analysis and/or impact assessment of a system and present them to meet the requirements of the application as described in the goal and scope of the study. Life cycle interpretation is also a process of communication designed to give credibility to the results of the more technical phases of LCA, namely the inventory analysis and the impact assessment in a form that is both comprehensible and useful to the decision-maker (EEA, 1997).

3.6.3. Life Cycle Assessment (LCA) Software

There is much software that analyses waste management with life cycle analysis. Some of the most widely used software in the world are (Dasic, 2007):

- Gabi
- SimaPro
- Quantis Suite Earth Smart
- Sustainable Minds
- Enviance System
- Open LCA

Apart from these widely used software, there are other using LCA tools in MSWM which are UMBERTO (Ifu Hamburg Gmbh), EASEWASTE (Environmental Assessment of Solid Waste Systems and Technology), and EASETECH (Environmental Assessment System for Environmental Technologies) whose former version of EASEWASTE models are developed by the Technical University of Denmark (DTU), IWM-2 (Integrated waste management-2), updated version of the IWM-1 (Integrated waste management-1), released by Procter and Gamble in 1995 (Khandelwal et al., 2019 and Sala et al., 2019). Furthermore, STAN (Substance flow Analysis) is a software that supports performing material flow analysis (MFA) according to the Austrian standard ÖNORM S 2096 (Material flow analysis - Application in waste management) (Cencic, et al., 2008).

In this thesis, SimaPro software, developed and distributed by Pre-Sustainability, is used. The software is designed as a science-based source of information and is widely adopted by companies, consultancies, and universities in more than 80 countries. The software can be used for sustainability reporting, assessing carbon and water footprints, facilitating product design, forming of environmental product declarations, and specifying basis performance indicators (Pre-Sustainability 2012).

4. MATERIALS AND METHODS

In this thesis, input and output analysis, GHG and energy production calculations as well as LCA of current MSWMS and alternative MSWM scenarios of the Istanbul megacity of Türkiye are done. This thesis aims to analyse the environmental effects of the current MSWM system of Istanbul and determine the environmentally best waste management scenario which reduces GHG emissions within the framework of the harmonization with European Union (EU) Green Deal, mitigate the load of the landfill as well as generate the highest energy.

Firstly, input and output analysis is performed by calculating the mass and energy balances of the waste disposal processes and the scenarios. In the next step, GHG emissions, the amount of avoided GHG and avoided energy obtained from recycling, composting, and anaerobic digestion processes have been calculated. Net GHG and net energy production are determined. Finally, all the scenarios are analysed with LCA to determine the most appropriate MSWMS in terms of climate change, ecosystem quality, and human health. For this scope, the impact category analyses GWP, SOD, FE, TE, PMF, HCT and LU is carried out using Recipe 2016 (Hierarchist) impact assessment methods with 9.3.0.3 version of the Sima-Pro. The functional unit is selected as 1 Mg of MSW, and characterization results are obtained at the midpoint level.

4.1. Study area

Istanbul is an intercontinental city located on two sides over two continents, one of which is the European side and the other is the Asian side. The European part is called the European side or Rumelia side and the Asian part is called the Asian or Anatolian side. The city comprises 39 districts 25 of which are located on the European side while 14 of the districts are located on the Anatolian side. The name and locations of the districts of the city are given in Fig.10.

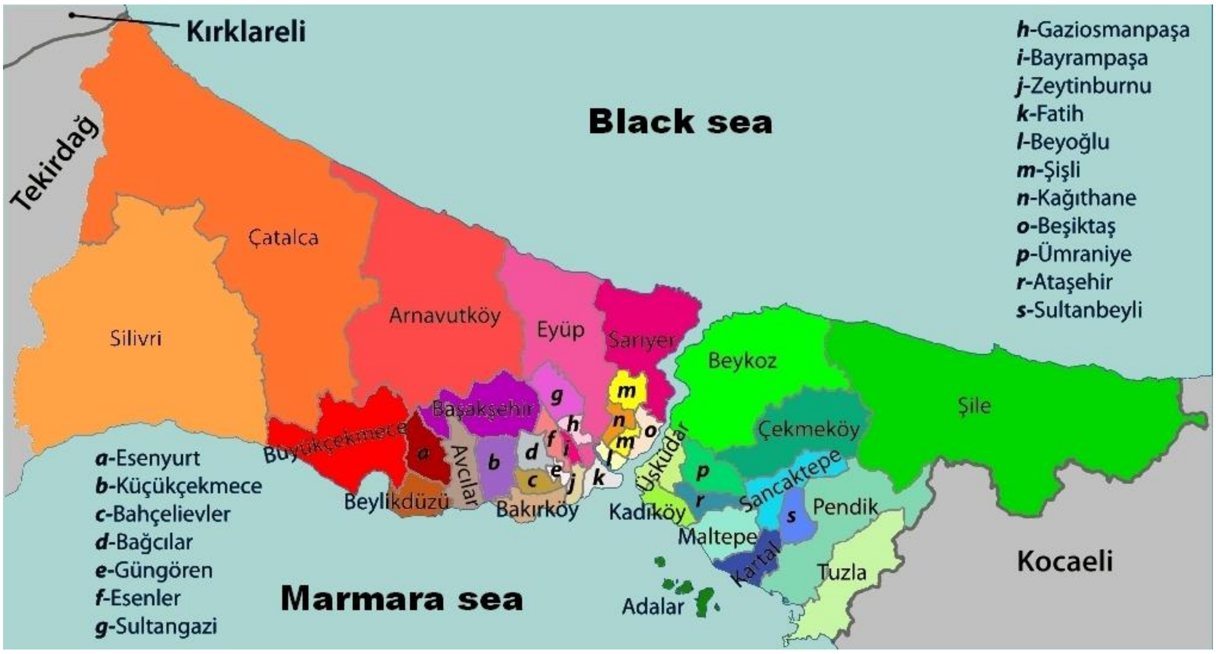

Figure 10. Map of the Districts in Istanbul (Wikimedia Commons, 2017)

4.2. Population Development

Istanbul is currently one of the most populous cities in the world, with a larger population than that of many countries. The city's population was 15,4 million in 2020, which corresponds to 18,4% of Türkiye population in the same year. In 2001, the population of the city was 10,3 million, which increased to 15,4 million by 2020. During this period, the population of Istanbul increased by approximately 49,5% over 20 years (Fig. 11).

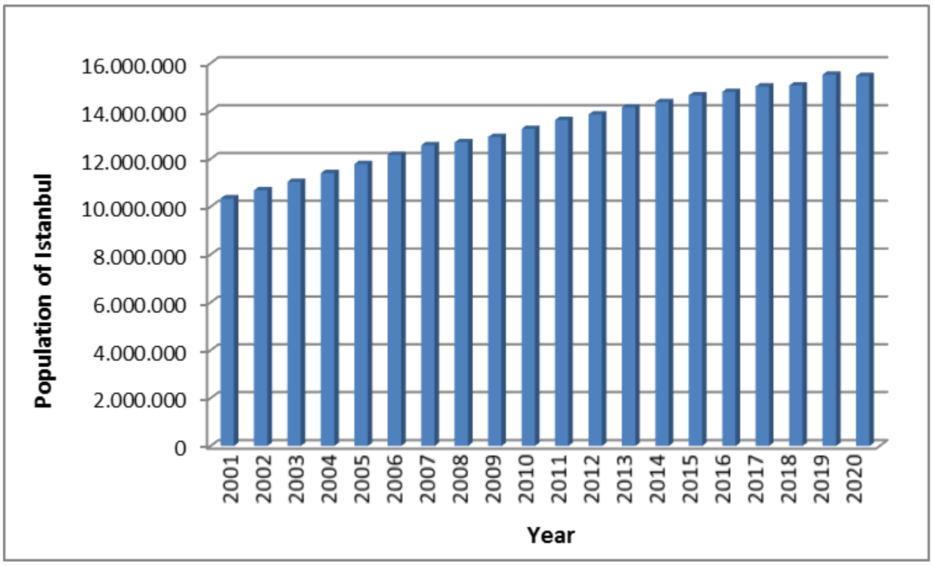

Figure 11. The population of Istanbul between 2001 and 2020 (TURKSTAT, 2021)

According to World Population Review (2023) projection data, it is predicted that the population of Istanbul will reach 16,2 million in 2025 and 17 million in 2030. Although the total population of Istanbul has increased over the years, the population growth rate has decreased. The growth rate of the country has stable values while the growth rate of the city has more variable values by years (Fig. 12).

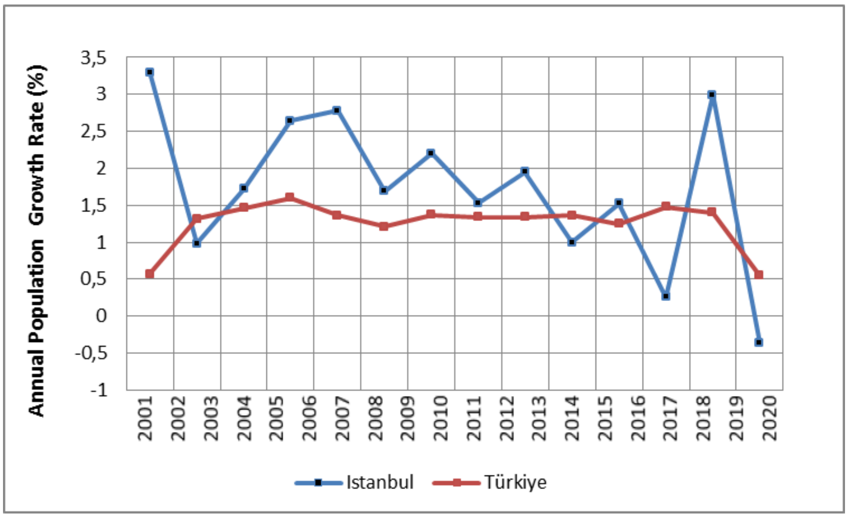

Figure 12. Annual Population Growth Rate of Istanbul and Türkiye by Years, 2001-2020 (TURKSTAT, 2021)

The population growth rate of Istanbul was at its highest, reaching 3,3%, during the period 2001-2007. Conversely, the rate reached its lowest point in 2020, with a decrease to 0,37%. In contrast, the country's growth rate ranged between 1,59% and 1,20%. The population growth rate of Türkiye experienced its lowest values between 2001 and 2007, ranging from 0,57% to 0,59%. However, it reached its highest value of 1,48% in 2018.

4.3. Current Municipal Solid Waste Management (MSWM) in Istanbul

The current MSWMS of Istanbul comprises source separation, collection, transport, recycling, composting, and sanitary landfill systems. The average MSW generation is 6.606.500 Mg/year in Istanbul in 2020. 83% of the amount of MSW is landfilled, 11% goes to composting plants and 6% of the waste is recycled (Fig.13) (ISTAC, 2020).

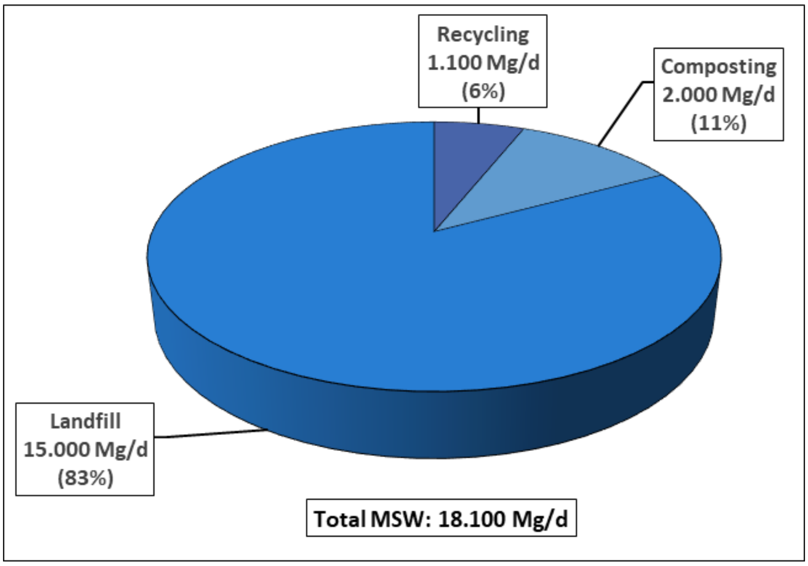

Figure 13. Municipal Solid Waste (MSW) Disposal Processes in Istanbul (ISTAC, 2020)

4.3.1. Solid Waste Production and Composition

According to TURKSTAT MSW data, 18.100 Mg/d of MSW is produced in Istanbul and this value corresponds to 1,17 kg/d per person in 2020. As shown in Table 11 that the highest amount of MSW collected in the years of 2016 and 2018 but the average amount of MSW collection per person was the highest value as 1,71 kg/d in 2001. It is also observed that, the average amount of collected waste per person in Istanbul is generally the higher than the average amount of collected waste per person in Türkiye.

Improvements in waste management practices (improved collection systems, recycling initiatives and waste reduction strategies) through the implementation of new waste management regulations and policies have resulted in a reduction in the specific waste quantity and an increase in the amount of recycled waste. The fact that the recycled waste has a lower density than the mixed collected waste is also a factor that causes decrease to the collected MSW in mass. In addition the conversion of volume data into mass data makes it difficult to compare statistical data.

Table 11. Population and Amount of MSW Collection in Istanbul by Years (TURKSTAT, 2021)

Years	Population of municipalities with waste services/Total municipal population	Amount of MSW collected in Istanbul	The average amount of MSW collected per person, Istanbul	The average amount of collected waste per person, Türkiye
	(%)	(Mg/y)	(kg/d)	(kg/d)
2001	100	6.112.454	1,71	1,35
2002	100	5.231.233	1,46	1,34
2003	100	5.374.854	1,5	1,38
2004	100	4.470.687	1,24	1,31
2006	100	4.771.604	1,05	1,21
2008	100	5.215.122	1,15	1,15
2010	100	5.731.003	1,2	1,14
2012	100	5.670.824	1,13	1,12
2014	100	6.064.688	1,16	1,08
2016	100	7.035.246	1,3	1,17
2018	100	7.042.585	1,28	1,16
2020	100	6.606.500	1,17	1,13

According to TURKSTAT (2021) data, the population provided waste service by the municipality is equal to the total municipal population. It means that the amount of production of solid waste is the same as the amount of collected municipal solid waste in Istanbul. When the amount of solid waste in Istanbul is compared with the solid waste in Türkiye, it is observed that the amount of solid waste produced per person in Istanbul is higher than in most of the years between 2001 and 2020. The amount of municipal waste is 1,17 kg/day per person in Istanbul and this value is above the average solid waste of Türkiye with the amount of 1,13 kg waste per person in 2020 (Fig.14).

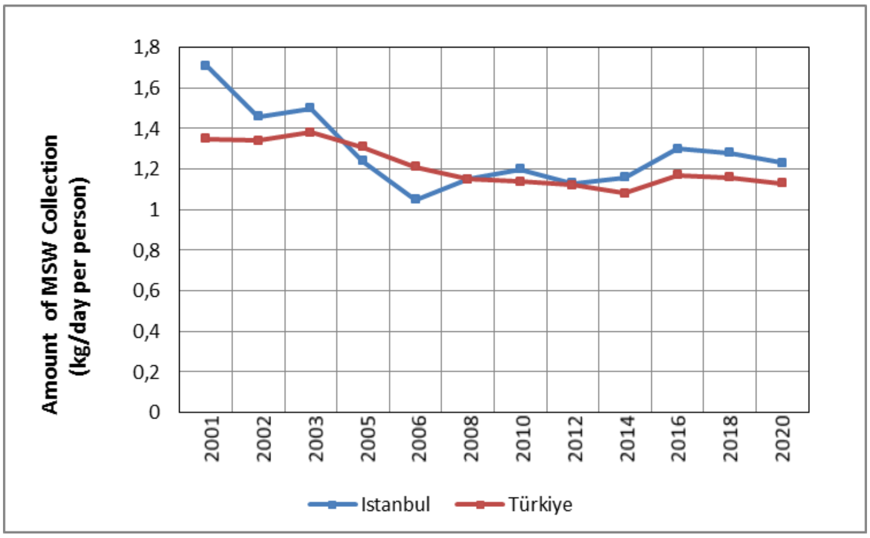

Figure 14. Amount of MSW Collection in Istanbul and Türkiye by 2001-2020 (TURKSTAT, 2021)

Solid waste characterization is the principle of determining the quantity and quality of waste in the region where the solid waste management system will be established. The content of solid wastes creates differences according to the level of development of the countries and shows great differences in urban, rural, or industrial regions within the same country. It is important to know the content of solid waste before starting to waste management plan. For this scope, the solid waste production and composition data of Istanbul are obtained from the ISTAC. The solid waste characterization study is conducted for Istanbul province by Istanbul Metropolitan Municipality, Directorate of Waste Management in 2018. The characterization study is performed by taking samples from 25 districts on the European side and 14 districts on the Asian side of the city. The waste samples are collected from 3 different income levels (high income, low income, commercial/bazaar region) from district municipalities and a characterization study is carried out at Kemerburgaz Recovery and Composting Facility on the European side and Kucukbakkalkoy Solid Waste Transfer Station on the Asian side. According to obtained solid waste characterization data; there is a significant difference between the waste samples from the bazaar and high-income regions and the samples from the low-income regions, especially in the recoverable waste content (ISTAC). MSW component values are obtained by average values of the characterization study that is carried out by taking samples from the European and Asian sides of the city (Fig.15).

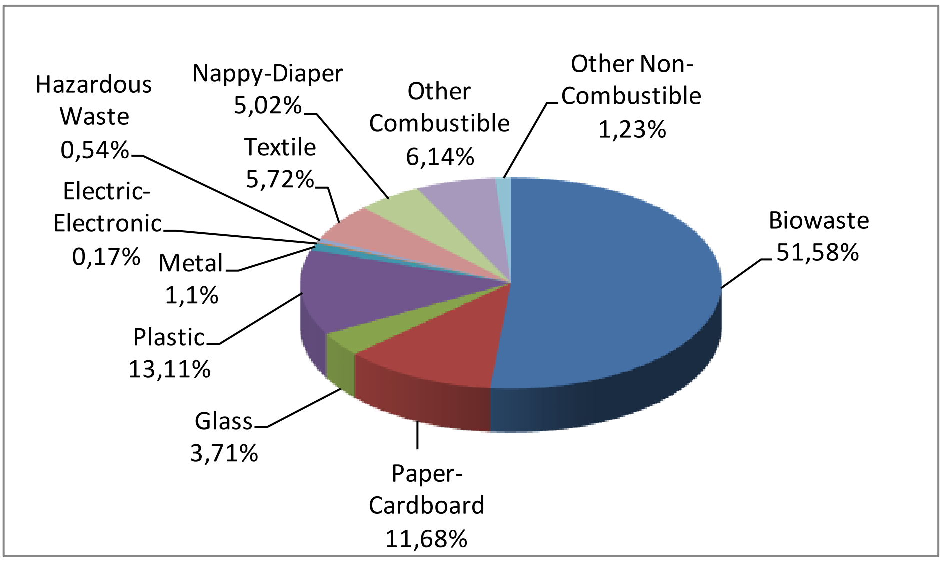

Figure 15. Istanbul Municipal Solid Waste (MSW) Fractions by weight (ISTAC, 2018)

The biowaste content (kitchen wastes, park-garden wastes) is found to be 51,58 % by weight in the samples. Plastic and paper-cardboard waste contents are the next most important materials with a proportion of 13,11% and 11,68%, respectively. The total proportion of recyclable wastes consisting of plastic, paper-cardboard, glass, metal, and electric-electronic waste is a remarkable result in the waste with a value of 29,77%. Another remarkable result of waste characterization study is the low percentage of metal with a proportion of 1,1%, this proportion consists of 0,432% Al (Aluminium), 0,648% Fe (Iron), and 0,02% Cu (Copper) metals. Electric-electronic and hazardous waste components are the lowest value in the total waste while textile and nappy-diaper waste composition is approximately the same value with the value of 5,72% and 5,02%, respectively.

4.3.2. Source Separation

A separate collection system is applied at the source for the reuse of used packaging wastes (paper-cardboard, metal, plastic, etc.) within the scope of “Regulation on Control of Packaging and Packaging Wastes" in Istanbul. The management of the separate collection and recovery of packaging waste within the boundaries of IMM was given to ISTAC which has initiated a recovery project to perform this task.

With this project, recyclable packaging wastes are collected by the owner separately from other waste. The recyclable wastes are left in front of the door, collected by special collection vehicles, and brought to the transfer station by district municipalities.

For this scope, 26 district municipalities work with İSTAC while 13 district municipalities carry out their work themselves or with CEVKO, IMM is to coordinate these activities.

Apart from these two collection systems, street collectors and scrap dealers have a significant role in the separate collection system in Istanbul. They have collected paper, plastic, glass, and metal from municipal solid wastes. Street collectors and scrap sellers buy used packaging from warehouses and workplaces or collect from street and waste containers. The waste recovered by street collectors is estimated to constitute 10% of the total waste and 25-30% of the recyclable waste. This type of recovery is unhealthy and illegal but this process is common in the city because they are very well organized (Yaman, 2011).

4.3.3. Collection and Transportation of Solid Waste

Collection and transportation of solid wastes constitute the most important part of the waste management system both in terms of environment and cost. The district municipalities are obliged to collect domestic and industrial wastes generated within the municipal boundaries and brought to solid waste transfer centres. The frequency of collection of solid wastes varies from district to district. In the district centres and the main roads, small vehicles collect ring waste by making ring voyages.

The general structure of the solid waste management system in the city is given in Fig.16. Mixed municipal solid wastes (MMSW) are left in specific areas in containers or bags and collected by collection vehicles. After that, the wastes come to transfer stations and send to landfill areas of the city. The mixed wastes, which are close to the landfill area, are transferred directly to the sites within the scope of the collection system. On the other hand, used packaging wastes (paper-cardboard, metal, plastic, etc.) are collected separately from the municipal wastes and recycled. Within the scope of the recycling, green or blue packaging waste bags are distributed to the residences, and they are collected on specific days and hours.

In some areas where the application is intensive, a packaging waste box is placed. Waste collected on certain days of the week is brought to separation facilities. The packaging wastes separated according to their types in the separation facilities are sent to recycling facilities and the recycling chain is completed. However, scrap dealers and individual collectors have an important role in the recovery of plastics, paper, glass, and metal from municipal solid waste. These individual collectors and scrap dealers purchase the used packaging from commercial units, markets, and business centres and reprocess these materials to sell directly to the industrial recycling facilities. In addition, scavenging and collection from waste bins is widespread activity in Istanbul. This type of collection and recovery process is a part of ‘‘unregistered’’ economic activity and makes it difficult to determine the actual collection and recovery figures (Berkun et al., 2011).

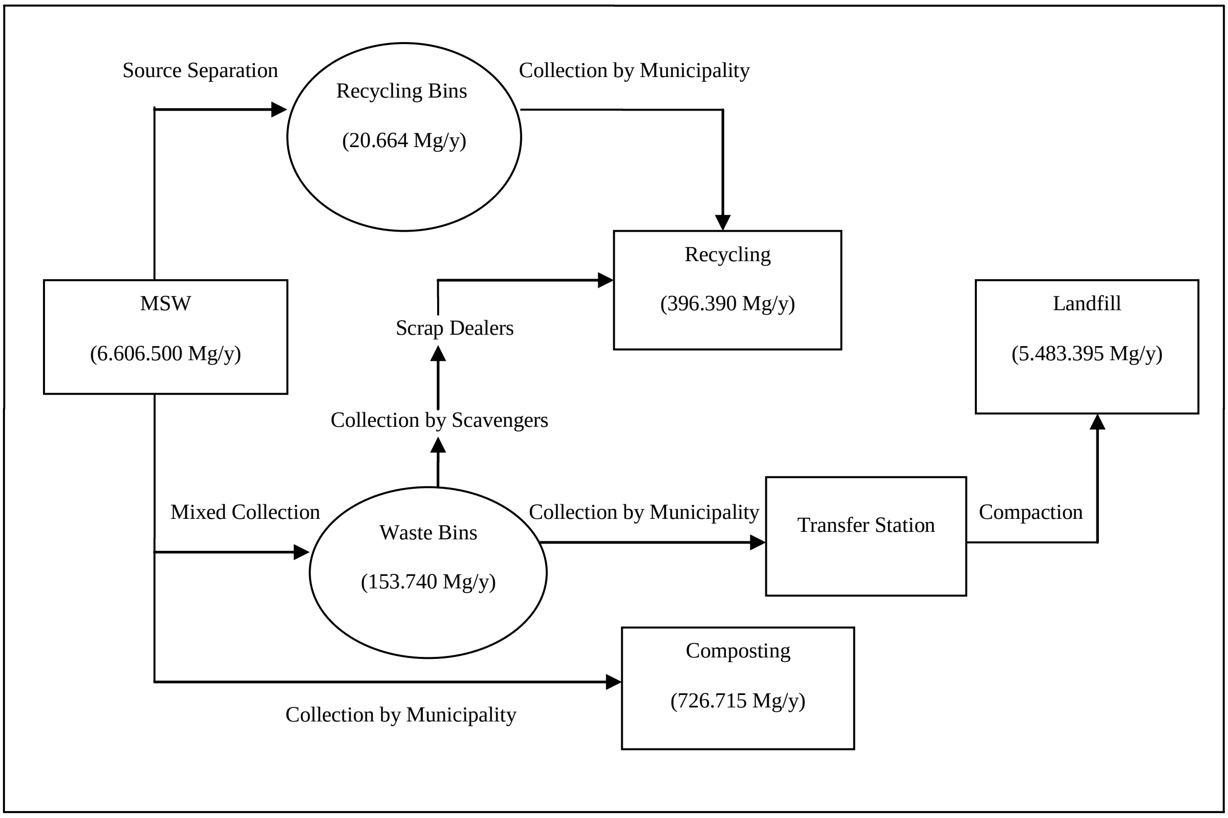

Figure 16. Current Municipal Solid Waste Management Flow Diagram for Istanbul (ISTAC and MOEU, 2020)

4.3.4. Transfer Stations

Due to the increasing number of residential areas in Istanbul with the effect of rapid population growth, the amount of waste produced has also been increasing day by day. To overcome this challenge the transfer stations are commissioned due to the costly and time-consuming transport of waste collected directly by district municipalities to the landfills. The wastes are collected from the houses, workplaces and bring to 8 transfer stations of IMM by the district municipalities.

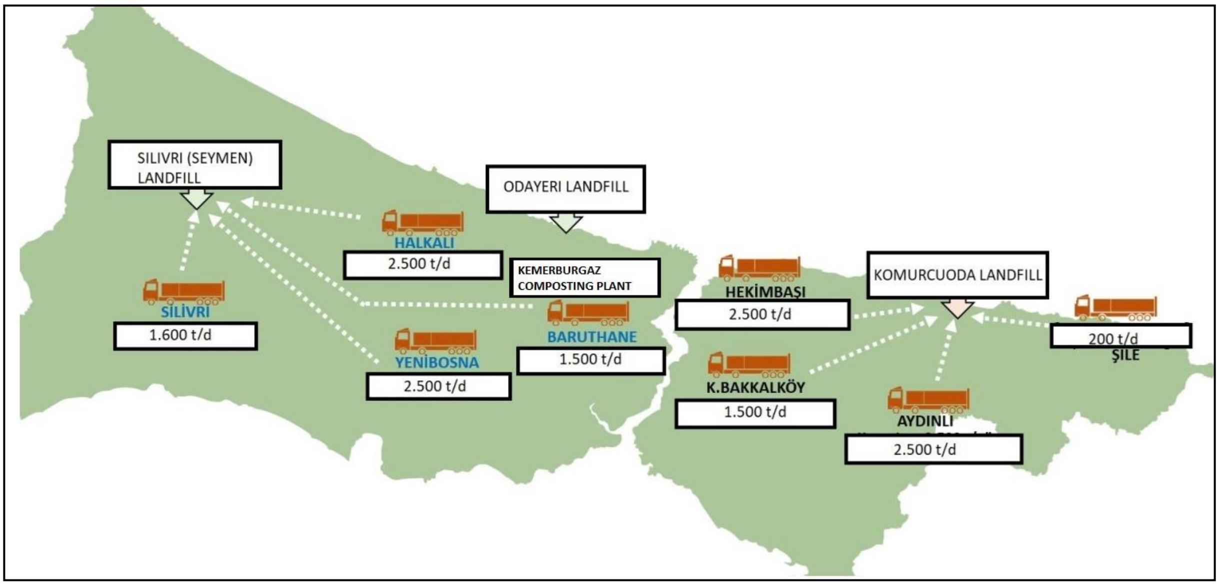

Figure 17. Istanbul MSW Transfer Stations and Landfill Sites Locations (Kaya et al., 2021)

Municipal solid wastes are collected by district municipalities and transferred to Yenibosna, Halkalı, Baruthane, and Silivri Waste Transfer Stations on the European side and Hekimbası, Aydınlı, Kücükbakkalkoy, and Sile Waste Transfer Stations on the Asian side (Table 12). The stations on the European side receive 10.000 Mg/d of MSW on average while 5.000 Mg/d are received on the Asian side. The location and capacity of the transfer stations and landfill areas are shown in Fig.17.

Table 12. Istanbul Municipal Solid Waste (MSW) Transfer Stations Data (IMM,2020 and Kaya et al., 2021)

European Side Transfer Stations	**Area**	**Capacity**	**Distance to Landfill Site**
	(m^2)	**(Mg/d)**	**(km)**
Silivri Transfer Station	11.950	1.600	26
Halkalı Transfer Station	35.000	2.500	88
Yenibosna Transfer Station	33.000	2.500	99
Baruthane Transfer Station	6.000	1.500	112
Asian Side Transfer Stations	**Area**	**Capacity**	**Distance to Landfill Site**
	(m^2)	**(Mg/d)**	**(km)**
Hekimbası Transfer Station	30.000	2.500	46
Kucukbakkalkoy Transfer Station	20.000	1.500	44
Aydınlı Transfer Station	48.000	2.500	55
Sile Transfer Station	11.000	200	33

In this way, by eliminating the transportation of small-capacity municipal waste collection vehicles to landfills over long distances; fuel saving is achieved, traffic density is reduced, and possible air pollution caused by exhaust emissions is prevented.

4.3.5. Sanitary Landfill Sites

There are two sanitary landfill sites (Class-2) in the Asian and European parts of Istanbul where municipality wastes are disposed of. (Eyup-Odayeri Waste Disposal Plant stopped receiving domestic wastes on 01.01.2018 due to the 3rd Airport Construction Project). According to 2018 database, 19.000 Mg/d of MSW is disposed of by landfill method; 11.600 Mg/d are disposed of in the Waste Disposal Plant located on an area of 227 hectares in Silivri, Seymen landfill area located on the European side of Istanbul while 7.400 Mg/d are disposed of in the landfill area located in an area of 233 hectares in Istanbul's Sile – Kömürcüoda located on the Asian side (Fig.18).

Figure 18. Istanbul Municipal Solid Waste (MSW) Landfill Areas (ISTAC, 2017)

The MSW disposal process such as operation, additional field construction, field monitoring and control, collection, and treatment of leachate, and landfill gas management in these landfill facilities are continuing according to national and international standards. The possible problems arising from disposal processes are also prevented with the formation of a permeability layer, laying, and compacting of wastes, the formation of intermediate cover, the collection and treatment of leachate and the protection of groundwater and surface water, the collection and control of the storage gas in the design and operation of sanitary landfills.

The most important problem in terms of environmental pollution in landfills is leachate generation. Leachate which arises from the content of solid wastes and contains the large number of pollutant parameters are formed by being exposed to several physical chemical and biological events by filtering through solid wastes. The leachate is formed because of the landfilled wastes and it pollutes the underground and surface resources significantly without precaution. The leachate is treated with Active Sludge Process in the biological treatment part of the MBR system while the cross flow ultrafiltration and nanofiltration methods are selected in the filtration part of the leachate treatment plant (ISTAC, Annual Report, 2018).

Every day, 2000 m^3 leachate is treated at the Odayeri landfill site on the European side and 1700 m^3 leachate is treated at the Kömürcüoda landfill site located on the Asian side according to discharge standards and transmitted to the city sewage.

4.3.6. Recovery and Composting Plant

MSW with high organic content is collected and processed naturally through microorganisms in a controllable manner in Kemerburgaz Recycling and Composting Plant in Istanbul since 2001. The recycling and composting facility that is illustrated in Fig.19 is established to evaluate the organic wastes in the mixed municipal wastes, to recycle the non-organic wastes that can be recycled, and to reduce the amount of waste sent to landfills. The foundations of the facility were laid in 1997 and it started operations in 2001. The plant is the biggest one in Türkiye and one of the most important composting plants worldwide and provides a processing capacity of 1.000 Mg/d of domestic waste. The compost and recycling plant consists of 4 units:

- Compost Unit
- Recycling Unit
- Pet-Plastic and Granule Unit
- RDF (Waste Derived Fuel) Unit

The types of waste collected from the districts are determined with the characterization studies carried out in Istanbul every year. Accordingly, the wastes of regions with high organic content and high rate of packaging waste, whereas the low rate of textile waste, are directed to the facility. Now, waste from Sarıyer, Beyoglu, Eyup, Sisli, and Besiktas districts is processed in the facility. Also, fruit and vegetable wastes collected from vegetable markets in Bayrampasa, branch and knot wastes coming from Metropolitan Municipality Cemeteries

Directorate, Parks and Gardens Directorate, other official institutions and organizations, and private individuals come to the facility separately from mixed municipal waste. These wastes are used by broken down to improve product quality.

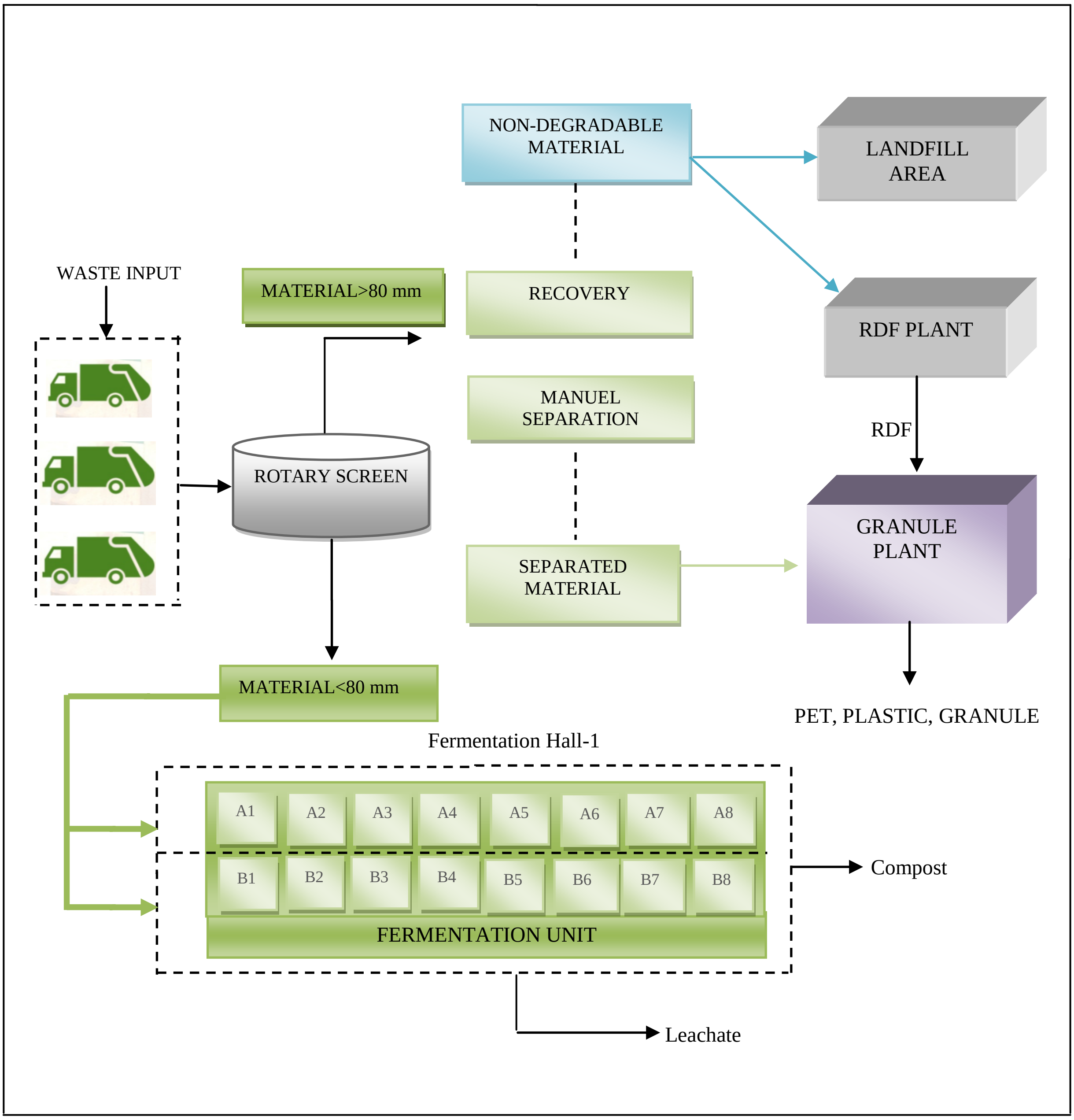

Figure 19. Kemerburgaz Recovery and Composting Plant Flow Diagram (ISTAC, 2019)

The bulky wastes (bed, seat, textile waste, construction-modification waste, automobile tire, etc.) are separated by waste handling machines and sent directly to Odayeri landfill area before the incoming wastes are fed to the system. After the bulky wastes are separated, suitable wastes are fed to 2 sieves with 80 mm holes in diameter. The bag opening blades break down the sealed bags as the waste goes through the sieves. The sub-sieved (<80 mm) wastes with high organic content are sent to the fermentation section after the metal-derived materials are separated on the magnetic belt while the wastes larger than 80 mm are sent to the recycling unit.

The composting section consists of 2 parallel halls with dimensions of 30 m x 190 m x 2.5 m and each hall has 8 areas. The waste is laid out in the 1st area of the first hall 3 days a week and the 1st area of the second hall on the other 3 days and maintenance is performed on Sundays. The waste remains in each area for 1 week and the mature material is taken out of the halls at the end of the 8th week. The temperature and humidity of the waste are controlled by the automation system during the composting and these values are maintained at desired intervals. The wastes whose composting process is completed are sieved through a 15 mm sieve in the final conditioning section. Sub-screen material is used as fine compost in green areas by the Metropolitan Municipality Parks and Gardens Directorate. In addition, sales are offered to private institutions and individuals.

The over-sieve material named coarse compost and has high calorific value is fed in the RDF unit after the metals are removed and the low-density materials are separated by air classifier. High-density materials are sent to Odayeri landfill area for use as cover soil. The material over 80 mm is sent to the recycling unit sorting section and extracted by hand. The extracted products are thrown into the waste cells. Paper, cardboard, sacks, cans, etc. materials that accumulate in waste cells are sold by pressing, Polypropylene, polyethylene, and polystyrene materials are processed in the granular and pet burring unit and recovered to the economy. Non-recycled waste in the recycling unit is sent to the RDF unit. After unsuitable materials in the wastes are broken in pre-crusher sizes below 250-300 mm, metal-derived materials are decomposed through a metal separator.

The remaining wastes and rough compost supplied to the RDF unit are crushed physically in a fine crusher to sizes of 0-30 mm and RDF product is obtained. The wastewater generated in the process is sent to the leachate treatment plant in Odayeri and Kömürcüoda Landfill areas by tankers. The foul-smelling ambient air caused by composting is delivered to the atmosphere after biofiltration.

It produces annually an average of 18.000 Mg of highly organic gardening compost which is used in the production of flowers in parks and gardens to revitalize the green texture of Istanbul.

4.3.7. Tasks and Authorizations

According to the "Metropolitan Municipality Law No. 5216"; IMM is obliged to perform the services related to the re-evaluation, storage, and disposal of solid waste from transfer stations, landfills, and other facilities excluding collection of solid wastes at source and transport to the transfer station, establish and operate the facilities for this purpose, required for these services, carry out services related to medical waste, to establish the necessary facilities for this, to operate or to make the necessary arrangements.

In this context, the Waste Management Directorate of IMM carries out the following services under the Department of Environmental Protection and Control:

- Operation of solid waste transfer stations in the city,
- Acceptance of domestic solid wastes brought to the solid waste transfer stations by district municipalities and transportation of domestic wastes from these stations to landfill areas,
- Construction, maintenance, repair, and operation of solid waste landfill facilities,
- Collection of medical wastes and operation of medical waste incineration and sterilization facilities,
- Operation of electric power generation plants from landfill gas,
- Operation of solid waste composting and recovery facilities,
- Disposal of defective, damaged, out-dated materials in accordance with the Solid Waste Control Regulation and disposal procedures in line with the demands from customs and private companies,
- Provide services related to sweeping, washing, and removing all kinds of visual pollution of the main arteries and squares in the city.

These obligations are fulfilled in a controlled manner by ISTAC which is owned by the IMM in Istanbul.

4.4. Municipal Solid Waste (MSW) Data Collection for Istanbul

The MSW component values are obtained by average values of the characterization study is carried out with IMM and ISTAC. Wet and dry waste components, recyclable and non-recyclable dry waste components are calculated according to the result of the characterization study (Table 13).

Table 13. Municipal Solid Waste (MSW) Fractions for Istanbul by weight (ISTAC, 2018)

Waste Type	MSW Components	Wet Waste Components (Biowaste)	Dry Waste Components	Recyclable Dry Waste Components	Non-Recyclable Dry Waste Components
	(%)	(%)	(%)	(%)	(%)
Kitchen Waste	50,56	50,56	-	-	
Park and Garden Waste	1,02	1,02			
Paper-Cardboard	11,68	-	11,68	11,68	-
Glass	3,71	-	3,71	3,71	-
Plastic	13,11	-	13,11	13,11	-
Metal	1,1	-	1,1	1,1	-
Electric-Electronic Waste	0,17	-	0,17	-	0,17
Hazardous Waste	0,54	-	0,54	-	0,54
Textile	5,72	-	5,72	-	5,72
Nappy-Diaper	5,02	-	5,02	-	5,02
Other Combustible	6,14	-	6,14	-	6,14
Other Non – Combustible	1,23	-	1,23	-	1,23
TOTAL	100	51,58	48,42	29,6	18,82

The amount of wet waste is equal to the amount of biowaste (515,8 kg) according to the characterization study and the remain of waste (484,2 kg) is considered recyclable and non-recyclable waste.

Recyclable dry waste calculations are made with the sum of the amount of paper-cardboard, glass, plastic, electric-electronic and metal components in the unit waste while non-recyclable dry waste calculations are made with the sum of the non-recycled waste such as hazardous waste, textile, and nappy-diaper in 1 Mg of the unit waste (Table 14):

- **Biowaste =** Kitchen waste + Park and garden waste = 505,6 kg + 10,2 kg = 515,8 kg
- **Recyclable Dry Waste =** Paper-cardboard + Glass + Plastic + Metal **+** Electric-electronic waste

= 116,8 kg + 37,1 kg + 131,1 kg + 11 kg + 1,7 kg = 297,7 kg

• **Non-Recyclable Dry Waste =** Hazardous waste + Textile + Nappy-diaper + Other combustible + Other non-combustible = 5,4 kg + 57,2 kg + 50,2 kg + 61,4 kg + 12,3 kg = 186,5 kg

Table 14. Waste Management Material Database (Löschau, 2006)

Waste	Ho	Water	Ash	LOI	C	H	O	N	S	Cl
	(wf)		(wf)		(waf)	(waf)	(waf)	(waf)	(waf)	(waf)
	(kJ/kg)	(%)								
Biowaste	18.800	62	15	85	49,5	7,7	38,1	3,1	0,3	1,2
Paper	14.200	25,5	18	82	45,5	6,6	47,1	0,2	0,2	0,3
Glass	0	0	100	0	0	0	0	0	0	0
Plastic	28.650	22	18	82	75	11,3	11	0,85	0,3	1,5
Metal	0	0	100	0	0	0	0	0	0	0
Hazardous Waste	0	10	100	0	67,5	12,5	17,5	0,5	0,5	1,5
Textile	18.700	23	7	93	54,2	7,1	33,1	3,9	0,4	1,3
Inert	0	10	100	0	0	-	-	0	0	0
Wood	17.000	17	0	100	48,2	6,5	43,7	1,1	0,4	0,1
Other	19.300	64	10	90	53	8,3	37	0,8	0,2	0,5

wf = Water free
waf = Water ash free

In addition to the characterization values of IMM and Istac, elemental analyse values of Istanbul MSW are calculated based on Löschau, (2006). Water (W), ash content, loss of ignition (LOI), the amounts of carbon (C), hydrogen (H), oxygen (O), nitrogen (N), sulphur (S), and chlorine (Cl) are calculated in the analysis process. Based on these calculations, the water content of the MSW is 43,6% while the dry waste composition is 56,4%. Based on 1 Mg of MSW; the amount of ash content and LOI are rounded 134 kg and 430 kg as water free. The water and ash-free values of C, H, O, N, S, and Cl are 233,3 kg, 35 kg, 148,3 kg, 8,3 kg, 1,28 kg, and 4,18 kg respectively (Table 15).

Table 15. Istanbul MSW Elemental Analysis Based on Dry Waste (Löschau, 2006 and ISTAC, 2018)

Waste	Waste	Water	Dry Waste	LOI	Ash	C	H	O	N	S	Cl
	(a)	(b)	(a-b)		(wf)	(waf)	(waf)	(waf)	(waf)	(waf)	(waf)
	(kg)										
Biowaste	515,8	319,8	196	166,6	29,4	82,4	13	63,5	5,2	0,5	2
Glass	37,1	0	37,1	0	37,1	0	0	0	0	0	0
Plastic	131,1	28,8	102,3	83,9	18,4	63	9,5	9,2	0,71	0,25	1,3
Paper-cardboard	116,8	29,7	87,1	71,4	15,7	32,5	4,7	33,7	0,14	0,14	0,22
Textile	57,2	13,1	44,1	41	3,1	22,2	3	13,6	1,6	0,16	0,53
Nappy-diaper (Other)	50,2	32,1	18,1	16,3	1,8	8,64	1,4	6,03	0,13	0,03	0,08
Metal	11	0	11	0	11	0	0	0	0	0	0
Electric-electronic	1,7	0,17	1,53	0	1,53	0	0	0	0	0	0
Hazardous waste	5,4	0,54	4,86	0	4,86	0	0	0	0	0	0
Wood (Other combustible)	61,4	10,4	51	51	0	24,6	3,3	22,3	0,6	0,2	0,05
Inert (Other non-combustible)	12,3	1,2	11,1	0	11,1	0	0	0	0	0	0
Total	1.000	435,8	564,2	430,2	134	233,3	34,9	148,3	8,38	1,28	4,18

Based on 1 Mg of MSW:

- **Water =** 436 kg/Mg
- **Dry Waste =** Total MSW – Water Content = 1000 kg – 436 kg = 564 kg/Mg
- **LOI =** 430 kg
- **Ash (wf) =** 134 kg

The calculated elemental analysis values (Table 15) for water, LOI, ash, C, H, O, N, and S in both kg and % units, are shown in Table 16.

Table 16. MSW Elemental Analysis Values of Istanbul (ISTAC, 2018 and Löschau, 2006)

Laboratory Analysis	Value	
	(%)	(kg/kg waste)
Water	43,6	0,436
LOI	43,0	0,430
Ash	13,4	0,134
Carbon (C)	23,33	0,233
Hydrogen (H)	3,5	0,035
Oxygen (O)	14,83	0,148
Nitrogen (N)	0,83	0,008
Sulphur (S)	0,128	0,001

4.5. LCA Method Definition

This thesis is carried out using the Recipe, 2016 (Hierarchist) impact assessment methods with the 9.3.0.3 version of the Sima-Pro. The time horizon of all the impact categories is 100 years from a hierarchist perspective. All MSW data used in this thesis are obtained from IMM and ISTAC.

4.5.1. Functional Unit

The functional unit for solid waste is accepted as 1 Mg due to the ease of comparison with other studies. Also, this is better for the calculation of the normalization factors, the mass, and energy balances.

4.5.2. Impact Categories

It is important to understand the implications of LCA studies from a broader, more inclusive perspective that considers not only the environment but also human health (Gursel, 2016). For this reason, LCA studies require the evaluation of the LCIA method that best characterizes the potential environmental impacts (Rigon, 2019).

In this thesis, the main and most appropriate impact categories relating to climate change, ecosystem quality, and human health are analysed. These categories are:

- Global warming potential (GWP)
- Stratospheric ozone depletion (SOD)
- Freshwater ecotoxicity (FE)

- Terrestrial ecotoxicity (TE)
- Particulate matter formation (PMF)
- Human carcinogenic toxicity (HCT)
- Land use (LU)

- **Global Warming Potential (GWP) (kg CO_2 eq):**

The GWP definition is the ability of different greenhouse gases to trap heat in the atmosphere. GWPs are based on the heat-absorbing ability of each gas relative to that of carbon dioxide (CO_2), as well as the decay rate of each gas (the amount removed from the atmosphere over a given number of years). GWPs can also be used to define the impact greenhouse gases will have on global warming over different periods or time horizons. These are usually 20 years, 100 years, and 500 years. For most greenhouse gases, the GWP declines as the time horizon increases (Recipe, 2016).

Characterization factors (CFs) of global warming are given for emissions into the air only. The impact of global warming at the damage level is expressed in kg CO_2-eq into air/kg identical to the midpoint category (Humbert et al., 2012). The midpoint CFs for global warming are expressed in kg CO_2-eq into air/kg and taken from the IPCC list (IPCC 2001, and IPCC 2007 for CH_4, N_2O, and CO). The GWP for a 100-year time horizon are used.

- **Stratospheric Ozone Depletion (SOD) (kg CFC-11 eq):**

The ozone layer is a band of natural gas called “ozone”. It is found between 9,3 and 18,6 miles (15-30 kilometres) above the Earth in what is known as the stratosphere, and it functions as a shield against harmful ultraviolet B (UVB) radiation emitted by the sun (Bucholz, 2016). Ozone depletion reflects the relative effect of total emissions of gases that deplete stratospheric ozone across the life cycle of a product used to deliver a unit of service (the functional unit), including end-of-life waste management. The characterization factor unit for ozone layer depletion is kg CFC-11 equivalents (Whiting & Azapagic, 2014).

European Environment Agency (EEA) has determined over 200 individual substances with a high ozone-depleting potential (ODP), including Chlorofluorocarbons (CFCs), Halons, Carbon tetrachloride (CTC), 1,1,1-Trichloroethane (TCA), Hydrochlorofluorocarbons (HCFCs), Hydrobromofluorocarbons (HBFCs), Bromochloromethane (BCM) and Methyl bromide (MB), all of which are referred to as 'controlled substances' (EEA, 2019).

The ODP expressing in kg CFC-11 equivalents is used as a characterization factor at the midpoint level. The ODP measures the amount of ozone a substance can deplete relative to CFC-11 for a certain time horizon and is highly correlated with the molecular structure of the ozone-depleting substances and especially the number of chlorine and bromine groups in the molecule, as well as the atmospheric lifetime of the chemical (Recipe, 2016).

- **Freshwater and Terrestrial Ecotoxicity (FE and TE) (kg 1,4-DCB):**

Freshwater (aquatic) ecotoxicity (FE) is used to represent potential adverse effects on organisms living in the aquatic environment from exposure to a toxic chemical (Swanson et al., 1997). FE may cause decreased aquatic plant and insect production, decreased biodiversity, and fish populations (Williams, 2009). The impact for this category arises mainly out of heavy metal emissions from leachate to water. They are especially high for leachate from slag (Olsson, 2015).

Terrestrial ecotoxicity (TE) is used to represent potential adverse effects on organisms living in the terrestrial environment from exposure to a toxic chemical (Swanson et al., 1997). TE may cause decreased production and biodiversity, and decreased wildlife populations (Williams, 2009). TE is dominated by pesticide emissions to agricultural soil as well as the use of both sulphuric acid and steam during the conversion process (Borrion et al., 2012). Exhaust from incineration, inorganic particles, diesel consumption (e.g., for transportation) and waste handling are the main factors causing impacts.

The toxicity potential (TP) is used as a characterization factor at the midpoint level for human toxicity, freshwater aquatic ecotoxicity and terrestrial ecotoxicity and it is expressed in kg 1,4 Dichlorobenzene (DCB) equivalents (Recipe, 2016). The time horizon is selected as 100 years.

- **Human Carcinogenic Toxicity (HCT) (kg 1,4-DCB):**

The human toxicological effect factors are derived for carcinogenic and non-carcinogenic effects separately, reflecting the change in lifetime disease incidence due to a change in intake of the substance. HCT of Recipe 2016 hierarchic scenario includes 844 carcinogenic substances to humans which are evaluated by the International Agency for Research on Cancer (IARC) (Recipe, 2016).

- **Particulate Matter Formation (PMF) (kg PM 2,5 eq):**

Particulate matter (PM) is a prevalent indicator of air pollution in a representative manner it consists of a complex mixture of solid and liquid particles of organic and inorganic substances suspended in the air and affects more people compared to any other pollutant. The major components of PM are sulphate, nitrates, ammonia, sodium chloride, black carbon, mineral dust, and water. Particles with a diameter of 2,5 microns or less are called PM 2,5 while the particles with a diameter of 10 microns or less are called PM 10. Although PM 10 can diffuse and settle deep inside the lungs, PM 2,5 are more health-detrimental particles that can penetrate the lung barrier and enter the blood system. Chronic exposure to these particles increases the risk of cardiovascular and respiratory diseases, as well as lung cancer (WHO, 2021).

The human intake of PM 2,5 is considered for the midpoint characterisation factors of fine particulate matter formation which is expressed in kg primary PM 2,5 equivalents. This category includes the effects of secondary aerosols from SO_2, NH_3, and NO_X as well as primary aerosols based on 100 years of time horizon (Recipe, 2016).

It is also reported that the fine PM fraction is generally formed of nitrate, sulphate, ammonium, black (elemental) carbon, a large number of organic compounds, and trace metals. PM 2,5 emissions which are mainly originated from the combustion of fossil fuels (electrical utilities and internal combustion engines), biomass burning (residential wood burning, wildfires, and other biomass burning such as agricultural burning), and ammonia emissions from agricultural operations (WHO, 2005)

- **Land Use (LU) (m^2a crop eq):**

Land use refers to the functional dimension (i.e., use) and corresponds to the description of areas in terms of their socio-economic purposes – how the area is used for urban activities, agriculture, forestry, etc. Land occupation refers to the use of a land cover for a certain period (Mattila et. al., 2011).

Although LU impact is analysed under three sub-categories which are agricultural land occupation (m^2a), urban land occupation (m^2a), and natural land transformation (m^2) in Recipe, urban land occupation (m^2a) is analysed in this thesis.

4.5.3. System Boundary

The system boundary includes source separation, metal separation, recycling of the waste and four different solid waste disposal methods which are landfill, composting, anaerobic digestion, and incineration. Emissions to air, water, and soil released from these disposal methods are also within the system boundaries. These emissions include the emissions arising from the landfill processes during energy production from LFG, the emissions arising from anaerobic digestion in energy production from biogas, and the emissions arising from directly incinerated of MSW, the emissions arising from compost production and recycling process. The construction phase of waste disposal facilities, collection, and transportation processes of the waste are excluded from the boundaries (Fig.20).

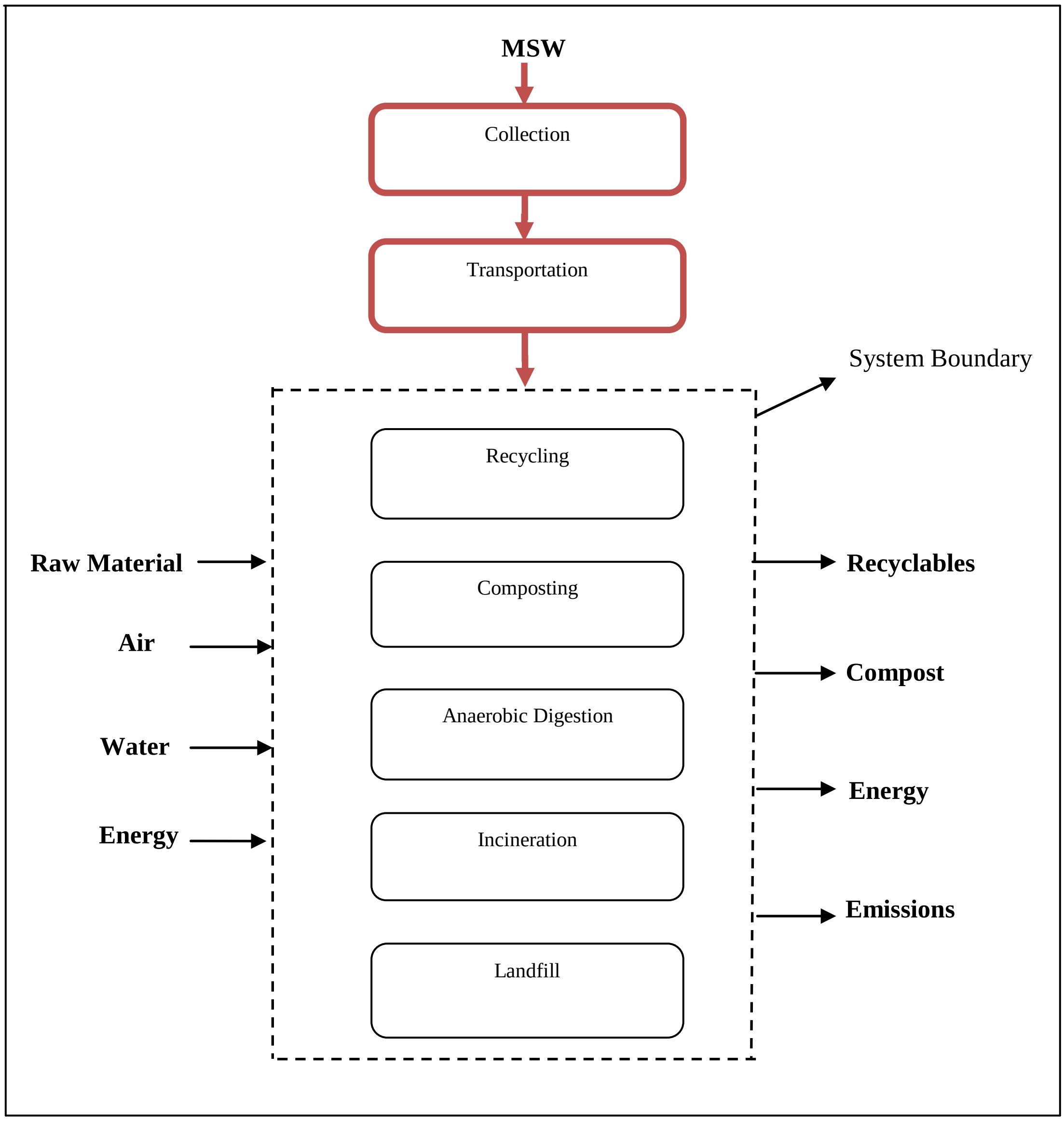

Figure 20. System Boundary

4.5.4. LCA Methodology with SimaPro

LCA characterization study is done in three main stages which are process, product, and life cycle stages.

Firstly, recycling, composting, anaerobic digestion, landfill, and incineration processes are defined in the 'Processes' tab in the 'Inventory' section. For this definition, the 'Others' heading of the 'Waste Scenario' sub-tab is used to avoid confusion. 'Others' is more comfortable to work with because it contains less used processes that are unlikely to be classified according to other headings. After opening the “Others” heading a new process definition is started by pressing the “New” button. For example, in defining the composting process 'treatment of kitchen and garden biowaste' composting method is selected for '1 kg' waste, and compost is selected in the 'Material/Waste type' header again, and 'Percentage' is defined as 100%. Thus, it is stated that all of the waste in this group is 'compost process' applicable waste. The reason for making this choice is to be able to process the waste regardless of its type since the type of waste is determined as 'compost'. In other words, 'compost' waste now includes all the organic waste and garden waste in MSW. This process is repeated for 'anaerobic digestion' as well. The only difference is that the method is designated as 'treatment of biowaste by anaerobic digestion'. All other values are the same. In the recycling process definition, the 'Recycle' sub-title of the 'Waste scenario' title is used and metal, plastic, glass, and paper, which are recyclable products, are defined separately by 'recycle' processes. After these preliminary definitions, 'compost', 'anaerobic digestion', and 'recycle' processes are ready for use.

After this stage, the scenarios are defined. For this purpose, the 'Others' heading in the 'Materials' sub-tab of the 'Processes' tab is used. This is the most important part because both the waste composition and all inputs and outputs should be defined here. For example, 1 Mg of waste is processed in the same place without any sorting after determining the waste for Basic Scenario-1, because all of the waste is disposed of with the landfill process in this scenario. The most important point here is to choose a waste type in the 'Waste type' title. After this definition, calculated values in the inventory analysis are entered in the avoided products and inputs and outputs section, and the scenario definitions are completed. The same procedures are carried out on Basic Scenario-2 as there is only the incineration process there. Separate definitions are made for different disposal processes for Basic Scenario-3 and the other scenarios because they contain more than one waste disposal process. The definition of waste compositions, disposal methods, and input/output values of all the scenarios are completed at this stage.

After all of the scenario definitions, the 'Product Stages' sub-tab of the 'Inventory' tab is switched. Landfill and incineration process data obtained from the Simapro database. Scenarios are defined with the quantities in the ‘Assembly’ sub-tab of ‘Product Stages’, the scenario data which is previously defined in the 'Processes' heading is used. Otherwise, the input/output values become meaningless. In this way, the process is closed in the 'Life cycle' sub-tab of the 'Product Stages' heading after making separate definitions for each scenario and the disposal methods of the wastes in each scenario. Here, the process is completed by selecting the scenario defined in the 'Assembly' heading and by marking which disposal method is used in the scenario.

After the disposal methods in the scenarios are defined separately in the 'Assembly' section, the same process is performed in the 'Life cycle' section. Thus, different life cycles are defined for the different disposal methods. After all of the completed definitions, a separate life cycle file is opened in the same tab, and all the previously defined disposal methods are entered in the 'Additional life cycles' section, and all of them are combined. After this definition, the LCA characterization results are obtained by selecting the ‘Recipe 2016 Midpoint (H)’ method from the 'Analyse' section.

5. DEVELOPING SCENARIOS, MASS, AND ENERGY BALANCE

5.1. Inventory Analysis of Disposal Methods

An inventory of MSW disposal alternatives are specified in the thesis should be created to choose the most environmentally appropriate disposal option. In this context, all the data and calculations related to the landfill and composting plant in Table 17 are obtained from Odayeri Landfill and Kemerburgaz Recovery and Composting plants operating in Istanbul while theoretical knowledge is used for incineration and anaerobic digestion methods.

The mass and energy balance calculations of the scenarios are made through the current mass balances of the compost and landfill disposal methods in Istanbul, while anaerobic digestion and incineration mass and energy balance calculations are based on literature studies.

Table 17. Odayeri Landfill Database (ISTAC, 2017)

	Amount of MSW	**Leachate Generation**	**Amount of MSW**	**Leachate Generation**	**Leachate Formation Coefficient (Leachate Formation / Waste Generation)**
Odayeri Landfill Database (2017)	**(Mg/y)**	**(m^3/y)**	**(Mg/d)**	**(m^3/d)**	
	4.028.312	1.205.190	11.036	3.301	0,29
	Amount of MSW	**Landfill Gas Generation**	**Electricity Consumption**	**Diesel Consumption**	**Electricity Generation**
	(Mg/y)	**(m^3/y)**	**(kWh/y)**	**(m^3/y)**	**(kWh/y)**
	4.028.312	146.608.824	59.722.222	1.211.165	280.265.310

5.2. Mass and Energy Balances, of Disposal Methods

5.2.1. Landfill Mass and Energy Balance

a) Landfill Mass Balance

The data for leachate formation, electricity, and diesel consumption in the landfill process are obtained from IMM and Istac, while the data on landfill gas formation is sourced from the literature. However, it is noted the landfill gas data received from the municipality does not reflect the real amount of the waste stored in that year.

- **Landfill Gas (LFG) Production**

LFG energy projects utilize proven technologies to capture LFG, which is a product of solid waste decomposition in landfills that contains approximately 50% of CH_4 and 50% of CO_2, both of which are greenhouse gases (GHGs). LFG has a heating value of about 500 British thermal units (Btu) per standard cubic foot (Scf), which is equal to 18,62 MJ/m^3, making it a valuable source of energy (USEPA, 2012).

For the purposes of this inventory analysis, it is assumed that LFG contains 50% of CH_4 and 50% of CO_2. The methane generation potential of landfilled waste and the degradable organic content of the waste are calculated based on the formulas provided in IPCC Guidance, which are given in Equations (Eq.) 1 and 2, respectively (IPCC, 1996).

$\mathbf{L_0}$ **=** Methane generation potential [MCF x DOC x DOC_F x F x 16 / 12 (Mg CH_4/Mg waste)] **(Eq. 1)**

MCF = Methane correction factor (fraction)

DOC = Degradable organic carbon [fraction (Mg C/Mg MSW)]

$\mathbf{DOC_F}$ **=** Fraction DOC dissimilated

F = Fraction by volume of CH_4 in landfill gas

Degradable organic carbon (DOC) is the organic carbon that is accessible to biochemical decomposition, based on the composition of waste. It can be calculated from a weighted average of the carbon content of various components of the waste stream. The following IPCC equation estimates DOC using default carbon content values. DOC_F is an estimate of the fraction of carbon that is ultimately degraded and released from solid waste disposal sites, reflecting the fact that some organic carbon does not degrade or degrades very slowly when deposited in solid waste disposal sites. The IPCC guidelines recommend a default value of 0,77 for DOC_F. The methane correction factor (MCF) accounts for the fact that unmanaged solid waste disposal sites produce less CH_4 from a given amount of waste than managed solid waste disposal sites. According to the IPCC guidelines, the MCF value is defined as ‘1’ for managed solid waste disposal sites, while the default value for unmanaged solid waste disposal sites is ‘0,6’ (IPCC, 1996).

In the inventory analysis calculations, DOC_F and MCF are accepted as 0,77 and 1, respectively.

DOC = (0.4 x A) + (0.17 x B) + (0.15 x C) + (0.3 x D)	**(Eq. 2)**

A = Fraction of MSW that is paper and textiles

B = Fraction of MSW that is garden waste, park waste or other non-food organic putrescible

C = Fraction of MSW that is food waste

D = Fraction of MSW that is wood or straw

The degradable organic waste characterization data of Istanbul are obtained from the MSW characterization data of Istanbul (Table 18).

Table 18. Degradable Organic Waste Fractions of Istanbul (ISTAC, 2018)

Degradable Organic Waste	% Fractions (by weight)
A= Paper and textile	17,25 (11,51 + 5,74)
B = Non-food organic putrescible	1,02
C= Food waste	0,7
D = Fraction of wood or straw	0,5

When using the values in Table 17 for Equation 2, the DOC content of the Istanbul MSW is found to be 14,82% by weight of the total MSW.

DOC (%) = (0.4 x 17,25%) + (0.17 x 1,02%) + (0.15 x 50,7%) + (0.3 x 0,5%) **=** 14,82 %

The methane generation potential (L_0) of the Istanbul MSW is determined to be 76,1 m^3 CH_4 per Mg of waste from Equation 1.

$\mathbf{L_0 =}$ MCF x DOC x DOC_F x F x 16 / 12

= 1 x 148,2 x 0,77 x 0,50 x 16/12 = 76,1 m^3 CH_4/Mg waste

MCF = 1 **DOC =** 148,2 kg/Mg waste (14,82%)

F = 0,50 (50% of CH_4 in LFG) $\mathbf{DOC_F =}$ 0,77

According to the IPCC methane generation potential (L_0) formula, 76,1 m^3 of CH_4 is generated from the disposal of 1 Mg of MSW using the landfill process. It is assumed that 40% of the generated CH_4 is sent to the energy production unit, while the remaining 60% of CH_4 is emitted into the atmosphere. Consequently, 30,44 m^3 of CH_4 is directed to the energy production unit, and 45,66 m^3 of CH_4 is released into the atmosphere.

$$\textit{LFG} \longrightarrow \textit{50\% } CH_4 + \textit{50\% } CO_2 \qquad \mathbf{V_{CH4}} = \mathbf{V_{CO2}} = 76{,}1\ m^3/Mg$$

$$\mathbf{V\ (LFG)}_{\mathbf{(Generation)}} = \mathbf{V_{CH4}} + \mathbf{V_{CO2}} = 76{,}1\ m^3/Mg + 76{,}1\ m^3/Mg = 152{,}2\ m^3/Mg$$

a) $\mathbf{V_{(CH4)}}$ **(Atmosphere)** = V_{CH4} x 0,60 = 76,1 m^3/Mg x 0,60 = 45,66 m^3/Mg

b) $\mathbf{V_{(CH4)}}$ **(Energy)** = $\mathbf{V_{CH4}}$ **x 0,40 =** 76,1 m^3/Mg x 0,40 = 30,44 m^3/Mg

These volumetric values are converted to mass values with equation as follows,

$$d = m/V \longrightarrow m = d \times V$$

d) $\mathbf{m_{(CH4)}}$ **(Atmosphere)** = $V_{(CH4)}$ (Atmosphere) x $d_{(CH4)}$ = 45,66 m^3 x 0,71 kg/m^3= 32,4 kg

$\mathbf{m_{(CH4)}}$ **(Energy)** = $V_{(CH4)}$ (Energy) x $d_{(CH4)}$ = 30,44 m^3 x 0,71 kg/m^3= 21,6 kg

e) $\mathbf{m_{(CO2)}}$ = $V_{(CO2)}$ x $d_{(CO2)}$ = 76,1 m^3 x 1,96 kg/m^3 = 149 kg

$\mathbf{d_{(CH4)}}$ **=** (16 g/mol) / (22,4 L/mol) = 0,71 g/L = 0,71 kg/m^3 $\mathbf{d_{(CO2)}}$ **=** (44 g/mol) / (24 L/mol) = 1,96 g/L = 1,96 kg/m^3

Leachate Production

Two important sources of leachate are the water content in the stored waste and the amount of water entering the area from outside. The amount of leachate caused by the stored waste is approximately 20% of the water content of the waste, which directly seeps out as leachate. The amount of water formed as a result of the decomposition of organic materials in the field is less important than the above two sources. The water entering the storage area from the outside is formed by the leakage of precipitation through the tank and the entry of surface waters and groundwater (due to not taking the necessary precautions) into the storage. There is no entry and exit from the underground water to the tank body because the floor area of the landfill is made impermeable. Furthermore, there is no surface water source near the landfill, and the amount of water that can come from here has also been ignored (MOEU, 2014).

In line with this information in the literature, it is concluded that the amount of leachate production is equal to the sum of the leaking of water content from the waste body and the amount of precipitation leaking into the waste storage (evaporation is ignored). Although the data contains the amount of leachate consisting of the daily waste amount, the amount of precipitation infiltrated into the landfill area is unknown. This input data has been calculated in line with the data in the literature. According to Odayeri landfill plant data obtained from ISTAC, leachate production is 3.301 m^3 per day due to landfilling of 11.036 Mg of waste.

These output values are calculated for 1 Mg of MSW per day with Equation 3 shown below. The leachate density is accepted as equal to the density of water (d Leachate = d $(H_2O)_{liquid}$ = 997 kg/m^3). This amount of leachate generation corresponds to 1.555 kg leachate per Mg of landfilled waste.

All the calculated mass balance input and output values of the landfill process, based on 1 Mg of MSW, are shown in Fig.21.

Precipitation to Leachate for 1 Mg MSW

Time: 100 years

Amount of waste: 1 Mg

Average landfill height (LH): 10 m

The density of waste (d_{Waste}): 0,9 Mg/m^3

Precipitation (P): 700 mm/year = 700 kg/m^2

Leachate generation rate: 20 % of Precipitation

Precipitation leakage (PL),

$V_{(PL)}$ **(m^3/ Mg waste) =** Amount of waste / $d_{(Waste)}$ / LH x P x Landfill generation rate **(Eq. 3)**

= (1 Mg) / (0,9 $Mg.m^3$)/ 10 m x 0,7 m^3/m^2 a x 100 a x 0,20 = 1,56 m^3/Mg

$m_{(PL)}$ **(kg/Mg) =** $d_{(Precipitation)}$ x V(PL) = 997 kg/m^3 x 1,56 m^3/Mg = 1.555 kg/Mg

$d_{(Precipitation)} = d_{(Water)}$ = 997 kg/m^3

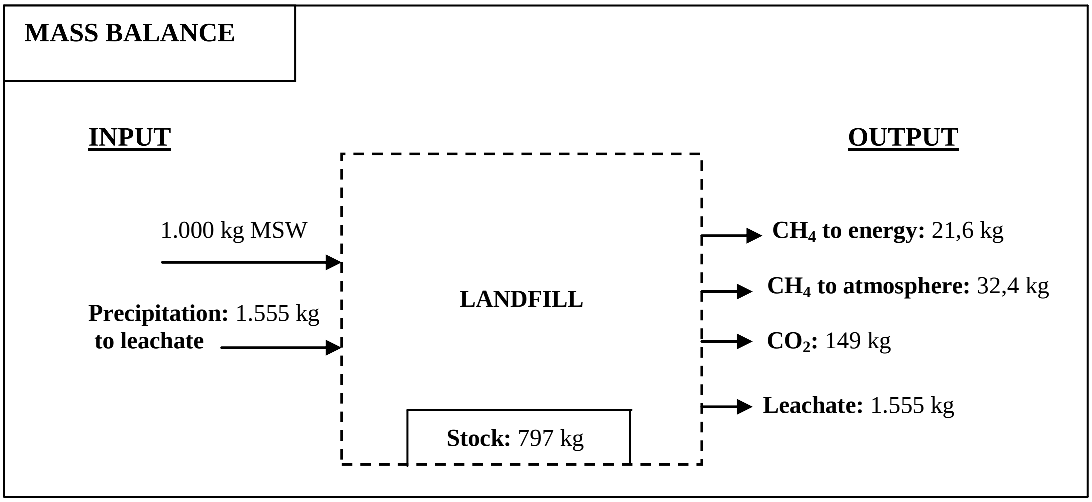

Figure 21. Landfill Process Mass Balance

b) Landfill Energy Balance

According to ISTAC (2017), the electricity and diesel consumptions are 59.722.222 kWh and 1.296.685 L, respectively, to produce 280.265.310 kWh/y electricity. These values correspond to 116,7 kWh of electricity and 0,53 L (0,43 kg) of diesel-oil consumption, respectively, for the generation of 116,7 kWh of electrical energy (Fig. 22).

Energy Input for Electricity Generation

Specific Electrical Energy Consumption;

Electrical energy consumption = (Annual electricity consumption / Annual electricity generation)

= (59.722.222 kWh/year / 280.265.310 kWh/year) = 0,21 kWh/kWh

Specific Diesel-oil Consumption (DC);

Diesel-oil consumption = (Annual diesel-oil consumption / Annual electricity generation)

= (1.296.685 L / 280.265.310 kWh) = 0,46 x 10^{-2} L/kWh

$\mathbf{m_{(Diesel\text{-}oil)}} = d_{(Diesel\text{-}oil)} \times V_{(Diesel\text{-}oil)} = 820\ kg/m^3 \times (0,46 \times 10^{-2}\ L/kWh \times 1 m^3/1000\ L) = 0,37 \times 10^{-2}\ kg/kWh$

$\mathbf{d_{Diesel\text{-}oil}} = 820\ kg/m^3\ (15^oC)$

Specific Electric Energy Generation

$$CH_4 + 2\,O_2 \longrightarrow CO_2 + 2\,H_2O$$

16 g   64 g   44 g   36 g

1 kg   4 kg $\longrightarrow$ *2,75 kg   2,25 kg*

21,6 kg + 86,4 kg $\longrightarrow$ *59,4 kg + 48,6 kg*

21,61 kg $\boldsymbol{CH_4}$ $\longrightarrow$ *21,6 kg x 55,5 MJ/kg x 0,278 kWh/MJ* **=** *333,4 kWh Energy*

Electric energy efficiency = *35%*

Electric energy generation = *333,4 kWh x 0,35 = 116,7 kWh*

m $\mathbf{(CO_2)}$ **(Atmosphere)** = CO_2 = 59,4 kg

m $\mathbf{(H_2O)}$ **(Atmosphere)** = H_2O = 48,6 kg

Energy Content of $\boldsymbol{CH_4}$ **=** *55,5 MJ*

1 MJ = 0,278 kWh

$\mathbf{CO_2}$**=** The amount of CO_2 generated because of energy production from methane

$\mathbf{H_2O}$**=** The amount of H_2O generated because of energy production from methane

Energy Balance for 116,7 kWh of Electricity Generation

Electric energy generation = 116,7 kWh

Diesel-oil consumption = $0{,}37.10^{-2}$ kg /kWh x 116,7 kWh = 0,43 kg

Electric energy consumption = (0,21 kWh/kWh) x 116,7 kWh = 24,5 kWh

Energy content of diesel-oil = $m_{(Diesel\text{-}oil)}$ x diesel-oil $_{(Energy)}$ = 0,43 kg x 11,86 kWh/kg

= 5,1 kWh

Facility losses = (Energy input) – (Energy output)

= (Energy potential + Energy of diesel-oil + Energy requirement) – (Energy production)

= (333,4 kWh + 5,1 kWh + 24,5 kWh) -116,7 kWh = 363 kWh – 116,7 kWh = 246,3 kWh

Net energy = Electric energy generation - Electric energy consumption

= 116,7 kWh – 24,5 kWh = 92,2 kWh

Diesel-oil $_{\mathbf{(Energy)}}$ = 11,86 kWh/kg

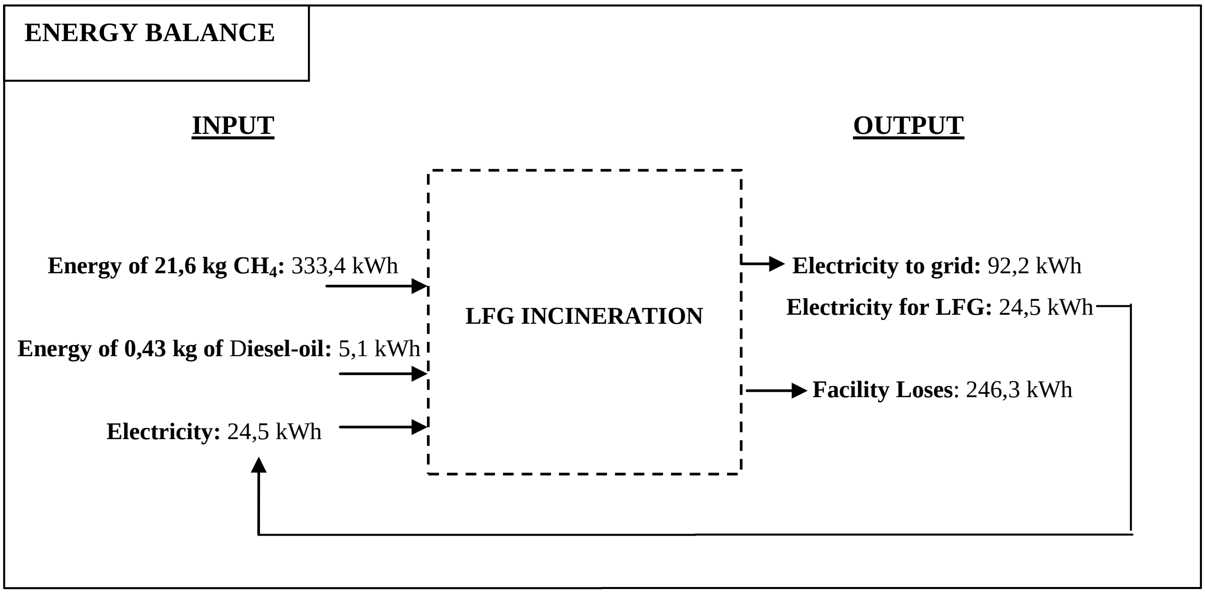

Figure 22. Landfill Process Energy Balance

Table 19 shows all the mass and energy balance values related to the landfill process, categorized as input and output flows.

Table 19. Landfill Process Input and Output Flows

Landfill	Value	Comment
Input		
MSW	1.000 kg	Mixed MSW
Precipitation	1.555 kg	
O_2	86,4 kg	Input for energy production from LFG
Diesel	0,53 L (0,43 kg)	
Electricity	24,5 kWh	
Output		
LFG	152,2 m^3	(50% CH_4 + 50% CO_2)
Leachate	1.555 kg	
CH_4 to energy	21,6 kg	
Electricity	116,7 kWh	35% of energy efficiency
Facility losses	246,3 kWh	
CH_4 to atmosphere	32,4 kg	Climate relevant
CO_2	149 kg	Biogenic
Off gasses		Combustion of 100 m^3 LFG
CO_2	59,4 kg	
H_2O	48,6 kg	

5.2.2. Composting Plant Mass and Energy Balance

Composting mass balance calculations are made according to the data obtained from ISTAC, and the resulting values are presented in percent units by mass (Fig. 23).

According to the mass balance of the Kemerburgaz Composting and Recycling Facility, 633,7 kg of 1 Mg of MSW goes into the composting process. From this amount, 163,8 kg fine compost, 144,5 kg coarse compost, and 102,4 kg leachate are generated, while the remaining 223 kg of the compostable waste evaporates as water (Fig. 23). The coarse compost is utilized as a daily cover layer in the landfill area, while the fine compost is stored and used by the municipality in parks and green areas.

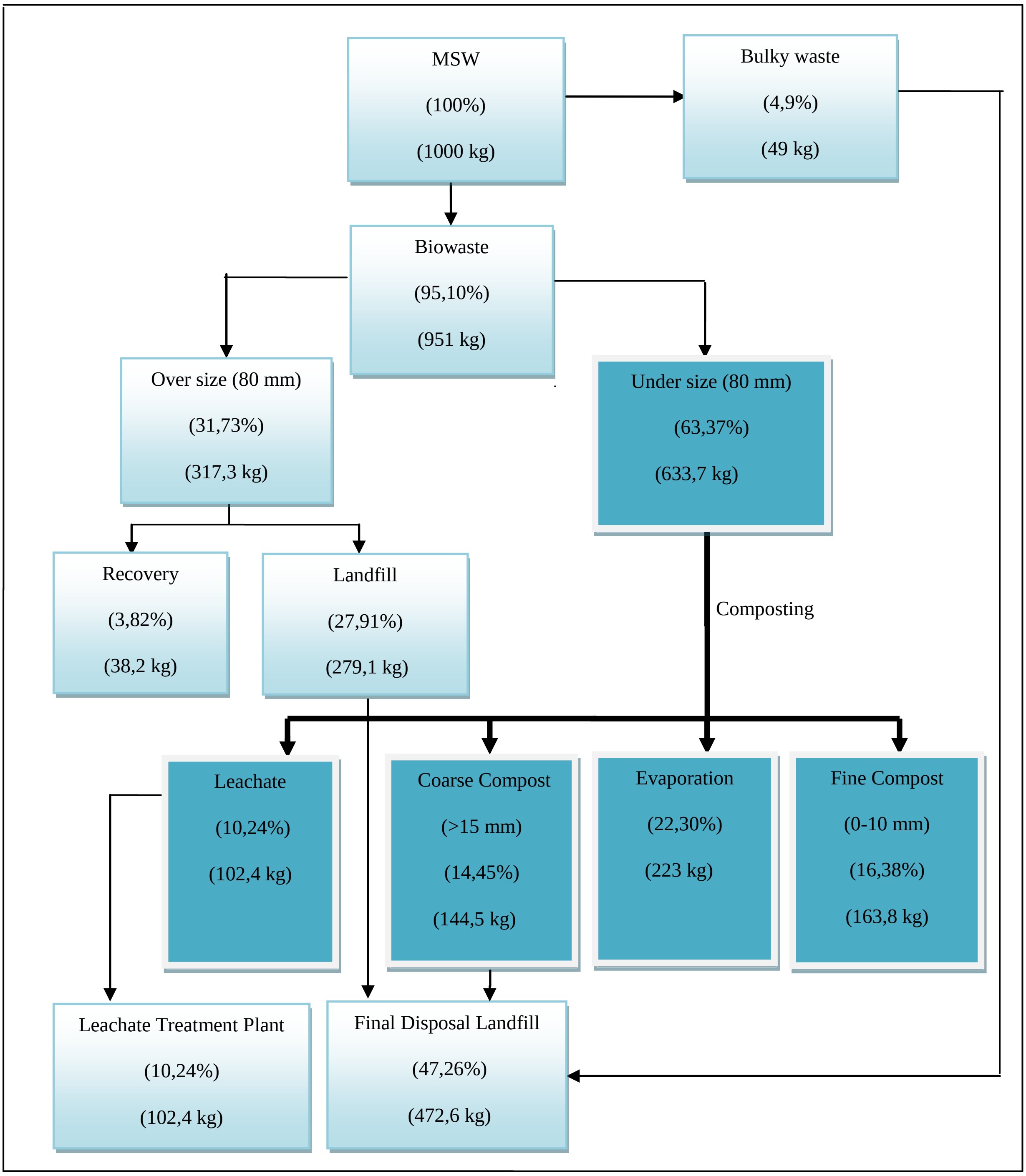

Figure 23. Kemerburgaz Recovery and Composting Plant Mass Balance Based on 1 Mg Biowaste Input (ISTAC, 2019)

For these calculations, 63,37% of the waste that enters the composting process is considered organic waste, and the mass balance values in Fig.23 are calculated based on 1 Mg of organic waste. These current composting values are than multiplied by the amount of 1 Mg of organic waste, resulting in 63,37 units of the waste, from which the new data is obtained according to 1 Mg of the biowaste (It is accepted that $d_{Leachate} = d\ (H_2O)_{Liquid} = 997\ kg/m^3$).

Composting Mass Balance

MSW Input = 1 Mg MSW (633,7 kg Biowaste)

Leachate:

L= (10,24 kg x 1.000 kg/Mg)/63,37 kg = 161,6 kg/Mg biowaste

$V_{(H2O)} =$ m/d = 161,6 kg /(997 kg/m^3) = 0,16 m^3

Fine compost (FC):

FC= (16,38 kg x 1.000 kg/Mg)/63,37 kg = 258,4 kg/Mg waste

Coarse compost (CC):

CC= (14,45 kg x 1.000 kg/Mg)/63,37 kg= 228 kg/Mg waste

Evaporation:

E= (22,3 kg x 1.000 kg/Mg)/63,37 kg = 352 kg/Mg biowaste

d (H_2O)$_{Liquid}$ = 997 kg/m^3

Approximately 2 g of oxygen is required per gram of decomposed organic matter. At the end of the reaction, approximately 2,2 g of carbon dioxide, 0,7 g of water, and approximately 0,08 g of ammonia are formed. In practice, the need for oxygen is variable and ranges from 1,5 g to 2,8 g O_2 per gram of decomposed organic matter, depending on the organic matter and the oxidation degree (Tabasaran et al., 2016). The amount of required energy for the composting plant is also obtained from the literature. Primary energy consumption is accepted as 52 MJ of electrical energy and 138 MJ of diesel energy, as determined by Springer (2011), for composting 1 Mg of biowaste. In this part of the thesis, only the mass balance of the composting process is evaluate; the energy balance of the process is not analysed because only heat is released as energy in the composting process (Table 20).

Table 20. Energy Inputs for Aerated Static Pile Composting

Amount of required oxygen and air for 1 kg of organic dry matter (ODM) Tabasaran et al., (2016)	**Oxygen Demand**	**Air flow volume**
	(kg)	**(L/h)**
	2,0	3,9-7,2
Amount of required energy for composting 1 Mg of biowaste Springer (2011)	**Diesel**	**Electrical Energy**
	(MJ)	**(MJ)**
	138	52

Composting plant (ISTAC)

Mass balance: (Based on 1 Mg MSW)

- 633,7 kg input in composting process

With the assumptions,

- **Water content of waste (W):** 60 %
- **Volatile solid (VS):** 70%
- **Biodegradation rate:** 50 %
- **Oxygen demand:** 2g O_2 per g decomposed ODM

Oxygen (O_2) requirement in mass:

$m_{(O2)}$ = (Biowaste input) x (Dry weight of MSW) x (VS) x (Biodegradation rate) x (O_2 demand) **(Eq. 4)**

= (633,7 kg) x (0,4) x (0,7) x (0,5) x (2 kg/kg) = (633,7 kg) x (0,28) = 177,4 kg

The required amount of oxygen is found to be 28% of the biowaste input, according to the equation. According to this calculation, 177,4 kg of O_2 is required for 633,7 kg of biowaste composting, and this value corresponds to 280 kg of O_2 requirement for 1 Mg of biowaste composting (Fig. 24).

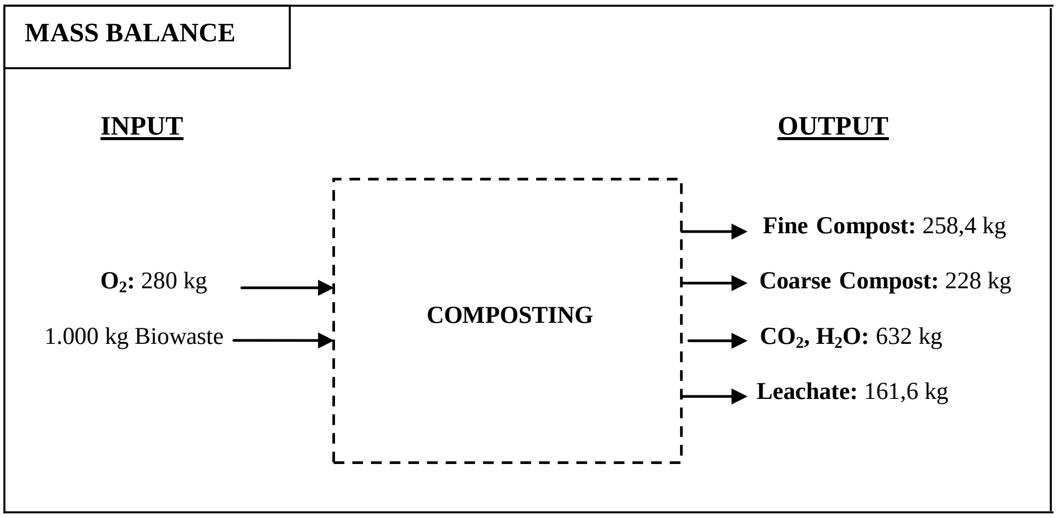

Figure 24. Biowaste Composting Mass Balance

All the mass balance values belonging to the composting process are shown as input and output flows in Table 21.

Table 21. Composting Process Input and Output Flows

Composting	Value	Comment
Input		
Biowaste	1.000 kg	(Kitchen waste, park and garden waste)
O_2	280 kg	
Diesel	38,3 kWh (138 MJ)	
Electricity	14,5 kWh (52 MJ)	(Springer, 2011)
Output		
Fine compost	258,4 kg	
Coarse compost	228 kg	
Leachate	161,6 kg	
CO_2, H_2O	632 kg	

5.2.3. Anaerobic Digestion (AD) Mass and Energy Balance

a) Anaerobic Digestion (AD) Mass Balance

Anaerobic digestion mass balance calculations are calculated according to Fig.25. This figure shows a mass balance for a full-scale thermophilic 'dry' digestion facility in Braunschweig, Germany, treating 20.000 Mg/year of source-separated biowaste (Kranert and Hillebrecht, 2000). In this calculation, it is accepted that leachate is equal to 21% of biowaste, digestate is equal to 67% of the waste, and biogas is equal to 12% of the waste in mass.

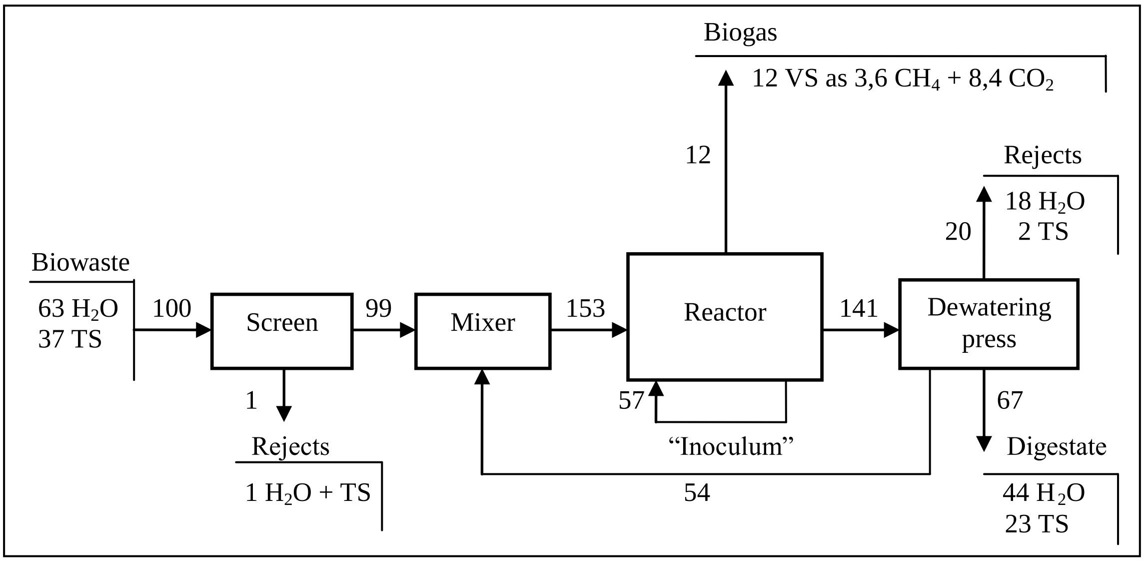

Figure 25. Mass balance for the 'dry' anaerobic digestion plant 'Braunschweig-Watenbuettel' treating (100 mass units) source-separated organic wastes. Based on Kranert and Hillebrecht (2000)

The values in Fig. 25 are for 100 units of waste by mass. In this thesis, the values in the figure are accepted as the percentage by weight. Therefore, 12% of the biowaste is accepted as biogas, and 67% and 21% of the biowaste is accepted as digestate and leachate respectively. After that, these percentages are multiplied by 1.000 and calculated for 1 Mg of biowaste (Fig. 26). The leachate volume is calculated with the assumption of the leachate density is equal to the water density (d: 997 kg/m^3).

Anaerobic Digestion Mass Balance

Anaerobically digested 1 Mg of waste,

- **Biogas:** 100 m^3/Mg waste (54% CH_4 + 46% CO_2)
- **Biogas to atmosphere:** 3 m^3
- **Biogas to energy:** 97 m^3
- **Density of biogas:** 1,2 kg/m^3 (20^oC)
- **Digestate:** 0,67 x 1.000 kg = 670 kg
- **Leachate:** 0,21 x 1.000 = 210 kg
- **Energy efficiency:** 80%

Biogas to energy (97 m^3)

$\mathbf{V}_{\mathbf{(Biogas)\ Energy}}$ = 97 m^3 (52,38 m^3 CH_4 + 44,62 m^3 CO_2)

$\mathbf{m}_{\mathbf{(Biogas)\ Energy}}$ = d $_{(Biogas)}$ x $V_{(CH4)\ Energy}$ = 1,2 kg/m^3 x 97 m^3 = 116,4 kg

Biogas to atmosphere (3 m^3)

$\mathbf{V}_{\mathbf{(Biogas)\ Atmosphere}}$ = 3 m^3 (1,62 m^3 CH_4 + 1,38 m^3 CO_2)

$\mathbf{m}_{\mathbf{(Biogas)\ Atmosphere}}$ = d $_{(Biogas)}$ x $V_{(CH4)\ Atmosphere}$ = 1,2 kg/m^3 x 3 m^3 = 3,6 kg

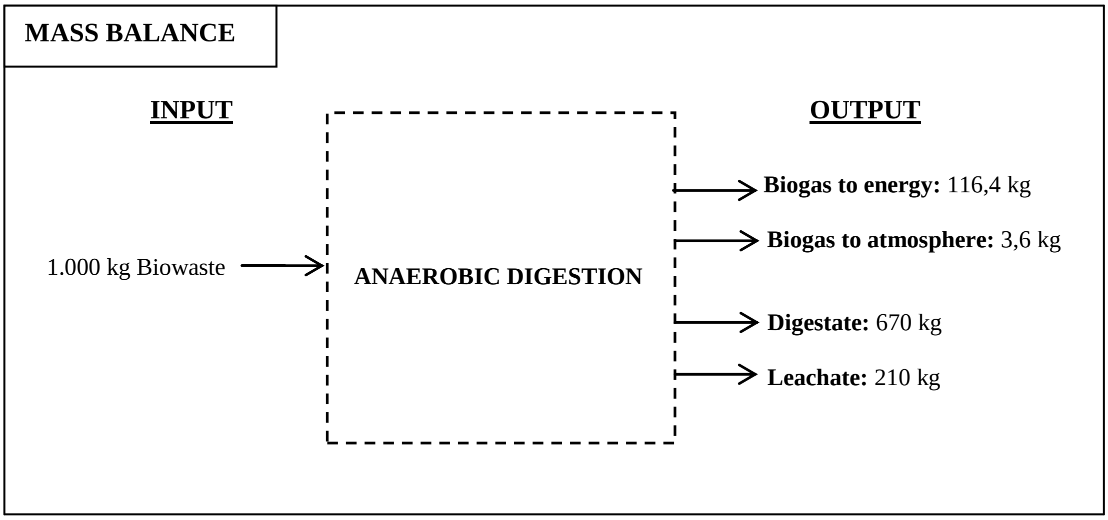

Figure 26. Anaerobic Digestion Mass Balance

b) Anaerobic Digestion (AD) Energy Balance

According to Moller et al. (2011), the typically composition of biogas from anaerobic digestion plants consists of 53-70% of CH_4 and 30-47% of CO_2 by volume. With the acceptance of the values given in this literature study, 100 m^3 of biogas consists of 54 m^3 (54%) of CH_4 and 45 m^3 (45%) of CO_2 in the inventory analysis. When these values in volume are converted to mass units; 100 m^3 of biogas in the volume corresponds to 120 kg of biogas formation and this value consists of 36 kg of CH_4 and 84 kg of CO_2. It is assumed that the biogas combustion plant is operated with 80% energy efficiency and 512 kWh of energy is produced by burning 80 m^3 of biogas. The data required for anaerobic digestion energy balance calculation are also obtained from the literature (Table 22).

Table 22. Energy balance of a fermentation plant: Biogas yield is 100 m^3/Mg of biowaste and calorific value is 6,4 kWh/m3 NTP (normal temperature and pressure, 20^oC and 1 atm) (Tabasaran et al., 2016)

Energy Balance	**kWh/Mg Biowaste** (100 m^3/Mg biowaste)
Energy Content	640
Heat and Electricity Generation Efficiency-Electrical (35%)	224
Heat and Electricity Generation Efficiency-Heat (55%)	352
Facility Losses (10%)	64
Electricity Requirement of Facility	45
Heat Requirement of Facility	50
Excess Energy	481

In this inventory analysis energy efficiency is accepted as 80% (35% as electricity, 55% as heat). Thus 555,8 kWh of energy generation is calculated by the combustion of 97 m^3 of biogas with a 620,8 kWh energy potential, while the facility losses are calculated as 163 kWh of energy (Fig. 27).

Anaerobic Digestion Biogas to Energy

- **Biogas:** 100 m^3/Mg waste (54% CH_4 + 46% CO_2)

Biogas to energy (97 m^3)

CH_4(Energy) = 0,54 x Biogas to energy **=** 0,54 x 97 m^3 = 52,4 m^3 ***d** $_{(CO2)}$ = 1,96 g/L = 1,96 kg/m^3*

$m_{CH4(Energy)}$ = $d_{(CH4)}$ x $V_{(CH4)}$ = 0,71 kg/m^3 x 52,4 m^3 = 37,2 kg   ***d** $_{(CH4)}$ **=** 0,71 g/L = 0,71 kg/m^3*

$$\underline{CH_4} + \underline{2\,O_2} \longrightarrow \underline{CO_2} + \underline{2\,H_2O}$$

16 g	*64 g*		*44 g*	*36 g*
1 kg	*4 kg*	$\longrightarrow$	*2,75 kg*	*2,25 kg*
37,2 kg + 148,8 kg		$\longrightarrow$	*102,3 kg +*	*83,7 kg*

(O_2) = 148,8 kg

(CO_2) $_{\textbf{(Atmosphere)}}$ = 102,3 kg

(H_2O) $_{\textbf{(Atmosphere)}}$ = 83,7 kg

Anaerobic Digestion Energy Balance

- **Energy potential** = Biogas converted to energy x Energy value of biogas

  = 97 m^3 x 6,4 kWh/m^3 = 620,8 kWh

- **Energy production =** Electric energy production + Heat energy production

  = 217,3 kWh + 341,5 kWh = 558,8 kWh

Electric energy production = 35% of Energy potential = 0,35 x 620,8 kWh = 217,3 kWh

Heat energy production = 55% of Energy potential = 0,55 x 620,8 kWh = 341,5 kWh

- **Facility losses =** (Energy input) – (Energy output)

  = (Energy potential + Energy of diesel-oil + Energy requirement) – (Energy production)

  = (620,8 kWh + 8,77 kWh + 92,2 kWh) – 558,8 kWh = 721,8 kWh – 558,8 kWh

  = 163 kWh

- **Energy requirement =** Electric requirement + Heat requirement **=** 43,7 + 48,5 = 92,2 kWh

Electric requirement = (Energy production x 45) /576 = (558,8 kWh x 45 kWh) /576 kWh = 43,7 kWh

Heat requirement = (Energy production x 50) /576 = (558,8 kWh x 50 kWh) /576 kWh = 48,5 kWh

- **Energy content of diesel-oil =** $m_{(Diesel\text{-}oil)}$ x diesel-oil $_{(Energy)}$ = 0,74 kg x 11,86 kWh/kg = 8,8 kWh

$m_{(Diesel\text{-}oil)}$ = $d_{(Diesel\text{-}oil)}$ x $V_{(Diesel\text{-}oil)}$ = 820 kg/m^3 x (0,9 L x 1m^3/1000 L) = 0,74 kg

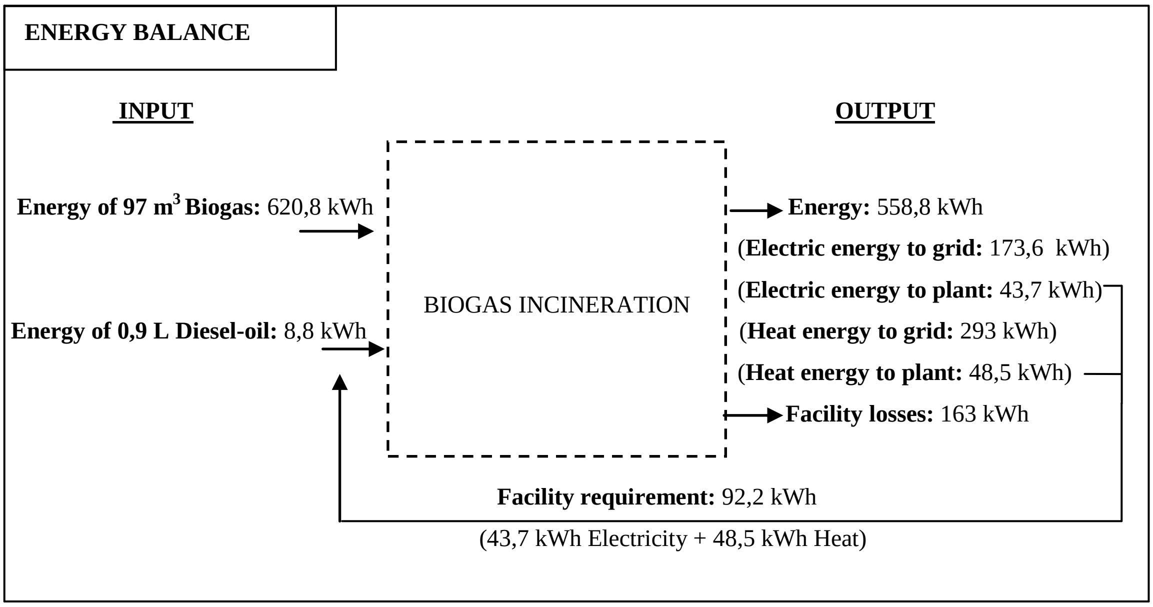

Figure 27. Anaerobic Digestion Energy Balance

All the anaerobic digestion process mass and energy balance values are shown as input and output values in Table 23.

Table 23. Anaerobic Digestion Input and Output Flows

Anaerobic Digestion	Value	Comment
Input		
Biowaste	1.000 kg	Kitchen waste, park and garden waste
Diesel	0,9 L	
O_2 requirement	148,8 kg	For energy production
Heat	48,5 kWh	
Electricity	43,7 kWh	
Output		
Biogas	100 m^3	(54% CH_4 + 46% CO_2)
Digestate	670 kg	
Leachate	210 kg	
CH_4 to energy	37,2 kg (52,4 m^3)	CH_4 in 97 m^3 biogas to energy
Heat	341,5 kWh	55% Heat efficiency
Electricity	217,3 kWh	35% Electricity efficiency
Facility losses	163 kWh	
CH_4 to atmosphere	1,15 kg (1,62 m^3)	CH_4 in 3 m^3 biogas to atmosphere
CO_2	84 kg	(CO_2 in 100 m^3 of biogas)
Off gasses		Combustion of 97 m^3 biogas
CO_2	102,3 kg	
H_2O	83,7 kg	

5.2.4. Incineration Mass and Energy Balance

a) Incineration Mass Balance

Consonni et al., (2005) developed alternative strategies for energy recovery from MSW in their study. According to this study, 588-807 kWh energy, 41 kg fly ash, and 187 kg bottom ash production are realized because of the incineration of 1 Mg of residual waste in the a WTE plant with a grate combustor.

The material balance of waste incineration developed by Quina et al., (2011) shows that the incineration process requires the injection of 4000-4500 m^3 air, and the volume of flue gas varies between 4.600–6.000 m^3 at the NTP (normal temperature and pressure, 20^oC and 1 atm) a per Mg of waste.

The amount of O_2 and air required for incineration of 1 Mg MSW, and the amount of exhaust gas (CO_2) generated because of the incineration process, minimum amount of combustion air "$l_{(min)}$", dry exhaust gas "$V_{(min)\ dry}$" and wet exhaust gas "$V_{(min)\ wet}$" amounts are calculated using empirical formulas based on Kranert (2017).

Stoichiometric oxygen demand, the minimum amount of combustion air "$l_{(min)}$", dry exhaust gas "$V_{(min)\ dry}$" and wet exhaust gas "$V_{(min)\ wet}$" amounts are calculated using empirical formulas based on Kranert (2017). The specific stoichiometric oxygen demand is found as 764,7 kg O_2/Mg. The $l_{(min)}$ dry, $V_{(min)}$ dry, and $V_{(min)}$ wet are found as 2,547 m^3, 2,45 m^3, and 3,37 m^3 respectively per kg of the waste.

Real firing systems cannot be operated with the stoichiometric minimum air volume due to insufficient mixing quality. An excess of air is required, which is called air ratio "λ" as the ratio of the amount of supplied air "l" to the minimum amount of air "l (min)". The excess air must be added to the minimum exhaust gas volumes (V min or V min $_{(wet)}$) to calculate the actual specific exhaust gas volumes (V min or V min $_{(wet)}$). In practice, MSW firing systems are usually operated with an air ratio of λ = 1,6 – 2,0 (Kranert, 2017).

Flue Gas (Wet) Composition

H_2O,

$$\underline{2H} + \underline{\tfrac{1}{2} O_2} \longrightarrow \underline{H_2O}$$

$$2\ kg + 16\ kg \quad 18\ kg$$

$$35\ kg + 280\ kg \quad 315\ kg$$

O_2: H x (32/12) = 35 kg x (16/2) = 280 kg

H_2O: H x (18/2) = 35 kg x (18/2) = 315 kg

CO_2,

$$\underline{C} + \underline{O_2} \longrightarrow \underline{CO_2}$$

$$12\ kg + 32\ kg \quad 44\ kg$$

$$233{,}3\ kg + 622{,}1\ kg \quad 855{,}4\ kg$$

O_2: C x (32 /12) = 233,3 kg x (32/12) = 622,1 kg

CO_2: C x (44/12) = 233,3 kg x (44/12) = 855,4 kg

SO_2,

$$\underline{S} + \underline{O_2} \longrightarrow \underline{SO_2}$$

$$32\ kg + 32\ kg \quad 64\ kg$$

$$1{,}3\ kg + 1{,}3\ kg \quad 2{,}6\ kg$$

O_2: S x (32/32) = 1,3 kg x (32/32) = 1,3 kg

SO_2: S x (64/32) = 1,3 kg x (64/32) = 2,6 kg

NOx,

$$\underline{N} + \underline{Ox} \longrightarrow \underline{NOx}$$

$$14\ kg + 16\ kg \quad 30\ kg$$

$$8{,}38\ kg + 9{,}57\ kg \quad 17{,}95\ kg$$

O_2: S x (16/14) = 8,38 kg x (16/14) = 9,57 kg

NO_X: N x (30/14) = 8,38 kg x (30/14) = 17,95 kg

H_2O + CO_2 + SO_2 + NO_X = 315 kg + 855,4 kg + 2,6 kg + 17,95 kg = 1.191 kg/Mg waste

Flue gas by mass comprises the sum of H_2O evaporated from the waste which is illustrated in Table 17. H_2O, CO_2, SO_2, and NO_X are determined in the stoichiometric calculations above, N (nitrogen) in the minimum amount of the air (l min) and the amount of supplied air (l) which is calculated with Eq. 6.

O_2 and Air Requirement

Based on stoichiometric calculations:

a) O_2 requirement (incineration) = O_2 (Carbon) + O_2 (Hydrogen) + O_2 (Nitrogen) + O_2 (Sulphur) - O_2 (Waste)

= 622,1 kg + 280 kg + 9,57 kg + 1,3 kg – 148,3 kg = 764,67 kg

- **O_2 (min) (kg/Mg waste) =** 764,7 kg/ Mg waste = 0,765 kg/kg waste

$\mathbf{V_{(O2)} = m_{(O2)}/d_{(O2)}} \longrightarrow V = (0{,}765 \text{ kg}) / (1{,}429 \text{ kg/m}^3) = 0{,}535 \text{ m}^3\text{/kg waste}$

b) $\mathbf{l_{min\,(dry)}} = (O_2 \times 100) / 21 = (0{,}535 \text{ m}^3\text{/kg} \times 100) / 21 = 2{,}547 \text{ m}^3\text{/kg waste}$ **(Eq. 5)**

$\mathbf{m_{min\,(dry)} = d \times V} \longrightarrow m = 1{,}293 \text{ kg/m}^3 \times 2{,}547 \text{ m}^3 = 3{,}29 \text{ kg/kg waste}$

$\mathbf{l} = (\lambda\text{-}1) \times l_{(min)} = (1{,}6 – 1) \times 2{,}547 \text{ m}^3\text{/kg} = 1{,}528 \text{ m}^3\text{/kg waste}$ **(Eq. 6)**

$\mathbf{m = d \times V} \longrightarrow m = 1{,}293 \text{ kg/m}^3 \times 1{,}528 \text{ m}^3 = 1{,}975 \text{ kg/kg waste} = 1.975 \text{ kg/Mg waste}$

c) Air input (m^3/kg waste) = $l + l_{min\,(dry)} = 1{,}528 \text{ m}^3\text{/kg} + 2{,}547 \text{ m}^3\text{/kg} = 4{,}075 \text{ m}^3\text{/kg waste}$ **(Eq. 7)**

$= 4.075 \text{ m}^3\text{/Mg waste}$

$\mathbf{m_{(Air)} = d_{(air)} \times V_{(air)}} = 4{,}075 \text{ m}^3 \times 1{,}293 \text{ kg/m}^3 = 5{,}269 \text{ kg/ kg waste} = 5.269 \text{ kg/Mg waste}$

Flue gas by mass comprises the sum of H_2O evaporated from the waste which is illustrated in Table 17. H_2O, CO_2, SO_2, and NO_X are determined in the stoichiometric calculations above, N (nitrogen) in the minimum amount of the air (l min) and the amount of supplied air (l) which is calculated with Eq. 6.

Flue Gas (Wet) Mass Composition

H_2O evaporated from the waste = 436 kg

H_2O + CO_2 + SO_2 + NO_X = 315 kg + 855,4 kg + 2,6 kg + 17,95 kg = 1.191 kg/Mg waste

N in the $l_{(min)}$ (by mass) = 0,77 x 3,29 kg = 2,533 kg/kg waste = 2.533 kg/Mg waste

l (by mass): 1.975 kg/Mg waste

- **Flue gas (by mass) =** H_2O + CO_2 + SO_2 + NO_X + N + l + H_2O (evaporated from the waste)

= 315 kg + 855,4 kg + 2,6 kg + 1,79 kg + 1.975 kg + 2.533 kg + 436 kg

= 6.135 kg/Mg waste

Density and Volume of Flue Gas (Wet)

Based on Formulas on Kranert (2017):

a) $\mathbf{V_{min\,(dry)}}$ **($\mathbf{m^3}$/kg waste) =** $1{,}87 \times C + 0{,}7 \times S + 0{,}8 \times N + 0{,}79 \times l_{min\,(dry)}$ **(Eq. 8)**

$= (1{,}87 \times 0{,}233\ m^3/kg) + (0{,}7 \times 0{,}001\ m^3/kg) + (0{,}8 \times 0{,}008\ m^3/kg) + (0{,}79 \times 2{,}54\ m^3/kg)$

$= 2{,}45\ m^3/kg$ waste

b) $\mathbf{V_{min\,(wet)}}$ **($\mathbf{m^3}$/kg waste) =** $1{,}87 \times C + 11{,}2 \times H + 0{,}7 \times S + 0{,}8 \times N + 1{,}25.\ W + 0{,}79 \times l_{min\,(dry)}$ **(Eq. 9)**

$= (1{,}87 \times 0{,}233\ m^3/kg) + (11{,}2 \times 0{,}035\ m^3/kg) + (0{,}7 \times 0{,}001\ m^3/kg) +$

$(0{,}8 \times 0{,}008\ m^3/kg) + (1{,}25 \times 0{,}43\ m^3/kg) + (0{,}79 \times 2{,}52\ m^3/kg) = 3{,}37\ m^3/kg$ waste

c) V (wet) ($\mathbf{m^3}$/kg waste) = l + V (min) wet = $1{,}528\ m^3/kg + 3{,}37\ m^3/kg = 4{,}898\ m^3/kg$ waste **(Eq. 10)**

d) d (V wet) = m (V wet)/ V (V wet) = $6.135\ kg/4.898\ m^3 = 1{,}25\ kg/m^3$

According to the calculations of flue gas (wet) mass composition which are done with formulas based on Kranert (2017), 6.135 kg flue gas (wet) and 167,5 kg bottom ash are formed as a result of incineration of 1 Mg MSW while 5.269 kg air and 33,5 kg water (for ash) are required (Fig. 28).

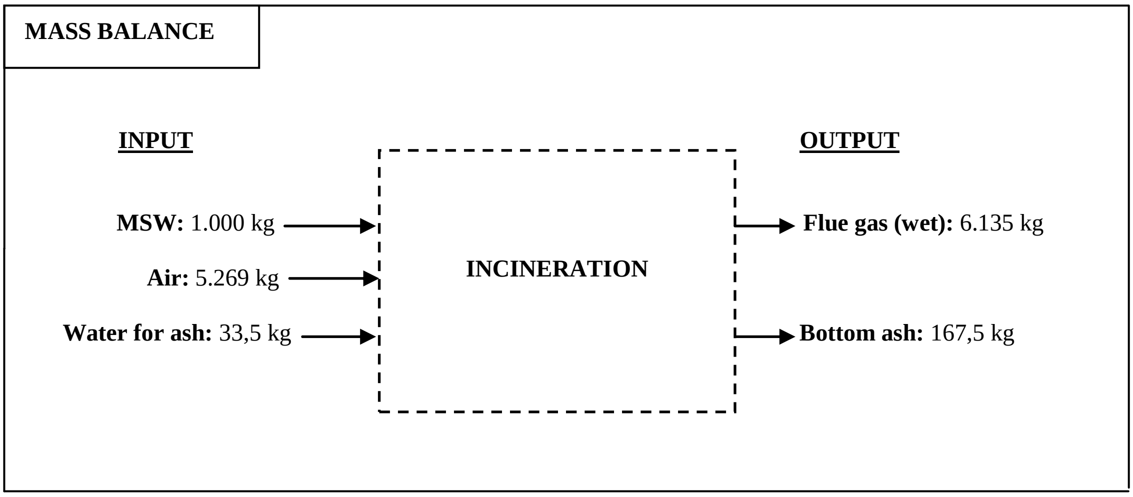

Figure 28. Incineration Mass Balance

b) Incineration Energy Balance

According to the Waste Incineration and Energy Generation Facility project of Istanbul, the energy will be produced and 75% by weight and 90% by volume from the solid waste amount will be reduced with this project. The planned facility is expected to operate for 8.000 hours per year. According to the project values, the MSW (lower heating value: 1.570 kcal/kg = 1,825 kWh/kg) to be brought to the facility will be incinerated through grid systems. In this method, wastes are directly incinerated without pre-treatment. The hot gases that are formed as the result of combustion will send to the waste heat boiler and steam with 232 MW (1.071 kWh) of energy value will be produced by burning 1 Mg of waste with 93% efficiency. The steam reaching 40 bar pressure and 400°C temperatures will send to the turbine and the turbine will rotate, and 85,8 MW (630 kWh) electricity generation will complete through the generator the remaining 441 kWh heat of low-pressure is cooled. It is planned to generate 78,8 MWh (578,74 kWh) electrical energy by incinerating 3.000 Mg of solid waste per day while 7 MWh (51,26 kWh) of the produced energy is used for the system. It is envisaged for the planned plant to operate 8.000 hours in a year (ISTAC, 2019).

In the inventory analysis of incineration energy balance the energy requirement of the incineration process is accepted equal to 27% of energy production of 1 Mg MSW (Economopoulos, 2009). However, it is assumed that the steam is produced with 95% efficiency and 35% of the produced steam converts to electrical energy (Fig. 29).

The upper calorific value (Ho) as water-free (wf) of each waste type is obtained from Löschau (2006), Ho (dry waste) is calculated with these values multiplied by the amount of dry waste based on MSW data of Istanbul determined by ISTAC (2018). Furthermore, the lower calorific value (Hu) of each waste category is calculated using Eq. 11 obtained from Kranert (2017), Hu (wet waste) is calculated by multiplying Hu values with the amount of waste. In conclusion, Ho (dry waste) and Hu (wet waste) are calculated as 9.893.515 kJ and this value is 7.962.565 kJ respectively based on 1.000 kg of MSW (Table 24).

$$\mathbf{Hu =} (Ho - (24{,}41 \times 8{,}94 \times F)) \times ((100 - W)/100) - (W \times 24{,}41) \qquad \textbf{(Eq. 11)}$$

Table 24. Lower and Upper Calorific Value of Istanbul MSW (based on Löschau, 2006, Kranert, 2017 and ISTAC, 2018)

Waste	Ho (wf)	Hu	Amount of Waste	Amount of Dry Waste	Ho (Dry Waste)	Hu (Wet Waste)
	(a)	(b)	(c)	(d)	(a x d)	(b x c)
	(kJ/kg)		(kg)		(kJ)	
Biowaste	18.800	4.992	515,8	196	3.684.800	2.574.874
Glass	0	0	37,1	37,1	0	0
Plastic	28.650	19.886,5	131,1	102,3	2.930.895	2.607.120
Paper-Cardboard	14.200	8.883,5	116,8	87,1	1.236.820	1.037.593
Textile	18.700	12.644,5	57,2	44,1	824.670	723.265
Nappy-Diaper (Other)	19.300	4.733,7	50,2	18,1	349.330	237.632
Metal	0	0	11	11	0	0
(Electric-Electronic)	0	-2.700	1,7	1,53	0	-4.590
(Hazardous Waste)	0	-2.700	5,4	4,86	0	-14.580
Wood (Other Combustible)	17.000	13.098,6	61,4	51	867.000	804.254
Inert (Other Non-Combustible)	0	-244,1	12,3	11,1	0	-3.002,4
Total MSW	-	-	1.000	564,2	9.893.515	7.962.565

Hu = Lower calorific value in kJ/kg   **1 kJ =** 0,001 MJ

Ho = Calorific value in kJ/kg   **1 MJ =** 0,278 kWh

W = Water content in %   **F =** Hydrogen content in %

Upper Heating Value (Ho) and Lower Heating Value (Hu)

- **Ho =** 9.893.515 kJ/0,5642 Mg dry waste x 0,001 MJ/kJ x 0,278 kWh/MJ = 4.875 kWh/Mg dry waste
- **Hu =** 7.962.565 kJ/Mg x 0,001 MJ/kJ x 0,278 kWh/MJ = 2.213 kWh/Mg wet waste

Incineration Energy Balance

- **Steam production (95% Energy efficiency) =** Hu x 0,95 **=** 2.213 kWh/Mg x 0,95 = 2.102 kWh
- **Electric energy production (35% Energy efficiency)** = Steam production x 0,35

  = (2.102 kWh x 0,35) = 736 kWh
- **Heat energy production** = Steam production – Electric energy production

  = 2.102 kWh – 736 kWh = 1.366 kWh
- **Electric energy consumption (27% of Electric energy production) =** 0,27 x 736 kW = 199 kWh
- **Facility losses =** (Energy input) – (Energy output)

  = (LHV + Energy requirement) – Steam production

  = (2.213 kWh + 199 kWh) – 2.102 kWh = 310 kWh
- **Avoided energy =** Heat energy + (Electric energy production – Electric energy consumption)

  = 1.366 kWh + (736 kWh – 199 kWh) = 1.903 kWh

1 MJ = *0,278 kWh*

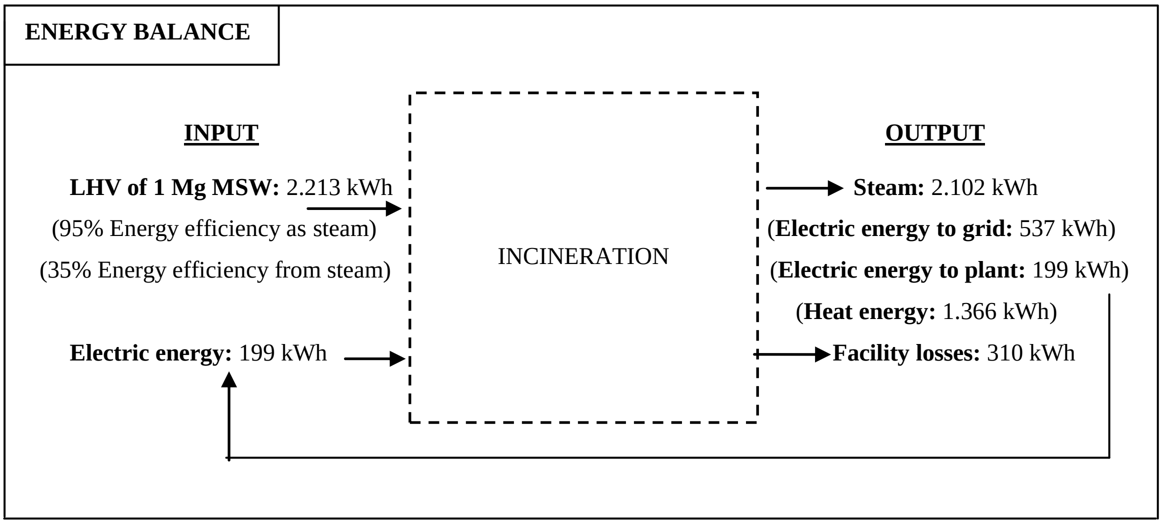

Figure 29. Incineration Energy Balance

All the incineration process mass and energy balance values are shown as input and output values in Table 25.

Table 25. Incineration Input and Output

Incineration	Value	Comment
Input		
MSW	1.000 kg	Mixed MSW
Total carbon of MSW	233,3 kg	23,33% of MSW
LHV	2.213 kWh (7.967 MJ)	
Air	5.269 kg	
Electricity	199 kWh	27% of Electrical energy production
Output		
Ash (Moist)	167,5 kg	
Electricity	736 kWh	35% of Steam (2.102 kWh)
Heat	1.366 kWh	65% of Steam (2.102 kWh)
Facility losses	310 kWh	
Flue gas (wet)	4.898 m^3	
H_2O	751 kg	
CO_2 (Biogenic)	547,4 kg	(From kitchen, paper, park and garden waste etc.)
CO_2 (Fossil)	308 kg	(From glass, plastic, rubber etc.)
SO_2	2,6 kg	
NO_X	17,95 kg	

5.3. Greenhouse Gas (GHG) and Avoided Products of Disposal Methods

Greenhouse gases (GHGs) warm the earth by absorbing energy and slowing the rate at which the energy escapes to space; they act like a blanket insulating the earth. The main greenhouse gases are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydro fluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6). Different GHGs can have different effects on the earth's warming. Two key ways in which these gases differ from each other are their ability to absorb energy (their "radioactive efficiency"), and how long they stay in the atmosphere (also known as their "lifetime") (Table 26) (USEPA, 2012).

Table 26. Global Warming Potential and Atmospheric Lifetime of GHGs (IPCC, 2014)

Greenhouse Gases	Chemical Formula	Global Warming Potential *AR5 (GWP-100)	Atmospheric Lifetime (years)
Carbon dioxide	CO_2	1	5-200
Methane	CH_4	28	12,4
Nitrous Oxide	N_2O	265	121
Chlorofluorocarbons (CFC11)	CCl_3F	4.660	45
Sulphur hexafluoride	SF_6	23.500	3.200

* SAR refers to the IPCC Second Assessment Report (1995) used for reporting under the UNFCCC.

* AR5 refers to the IPCC Fifth Assessment Report (2014)

GHG emissions resulting from energy production are composed of emissions from the combustion of LFG for electricity generation in the landfill process, it is generated by the combustion of biogas for heat and electrical energy production in the anaerobic digestion process, and it is generated by direct combustion of waste in the incineration process. These values resulting from energy production are taken from the literature.

The waste sector is not only responsible for GHG emissions but also contributes to avoiding GHG emissions. In the waste sector, GHG emission reduction is achieved through material (reuse, recycling, composting, etc.) and energy (biogas, electricity, and heat generation) recovery and thus an environmental benefit accounted for as avoided emissions. Energy can be generated as a co-product by waste treatment facilities. If this electricity is sold to the grid, it is considered to contribute to avoiding the emission of GHG. Avoided emission amount is obtained by evaluating the amount of energy produced from waste (GHG Protocol, 2013).

5.3.1. Recycling: GHG and Avoided Products

GHG production and avoided products (avoided energy and avoided GHG) values of recyclable waste including glass, plastic, paper cardboard, Fe-metals, aluminium, and copper are obtained from Probas (2021), Regensburg (2008), and Umweltbundesamt (2010). The percentage of material used in primary and secondary production, cumulative energy consumption (CEC), GHG production, avoided energy, and avoided GHG emissions in the primary and secondary production of the recyclables are illustrated in Table 27.

Table 27. Savings (CEC and GHG emissions) through secondary production of marketable intermediate products from secondary raw materials compared to primary production (Probas, 2021, Regensburg, 2008, and Umweltbundesamt, 2010)

	Primary Raw Material	**Secondary Raw Material**	**CEC**	**GHG Emissions**	**Avoided Energy**	**Avoided GHG**
	(%)		**(MJ/Mg)**	**(kg CO_2 eq)/Mg**	**(MJ/Mg)**	**(kg CO_2 eq/Mg)**
GLASS						
Primary production of green container glass	95		10.670	921		
Secondary production of green container glass		80% Broken Glass	7.270	506	3.400	415
PLASTICS						
PET beverage bottles, primary production	100		105.700	3.495		
PET beverage bottles, secondary production		30	78.700	2.685	27.000	810
PAPER-CARDBOARD						
Primary fibre paper	100		18.000	-		
Recycled Paper		100	7.200	-	10.800	160
FE-METALS						
Crude steel primary production		5% Own scrap	27.400	2.370		
Crude steel secondary production		30% Scrap Content	21.700	1.876	5.700	494
ALUMINIUM						
Aluminium, primary	100		140.700	11.904		
Aluminium, secondary		32,4% Process Scrap 67,6% Old Scrap	16.122	1.036	124.578	10.868
COPPER						
Copper, primary	100			50.438	2.874	
Copper, secondary		100		23.107	1.699	1.175

Recyclable Materials in Total 297,7 kg Recyclable

- **Paper-Cardboard =** 116,8 kg
- **Glass =** 37,1 kg
- **Plastic =** 131,1 kg

  PET = (9,7 % of Total Plastic) = (9,7 x 131,1 kg)/100 = 12,7 kg

  LPDE (Other plastics) = (90,3 % of Total Plastic) = (90,3 x 131,1 kg)/100 = 118,4 kg
- **Metal =** 11 kg

  Al = 39,3 % of Metal = (39,3 x 11 kg)/100 = 4,32 kg

  Fe = 58,9 % of Metal = (58,9 x 11 kg)/100 = 6,48 kg

  Cu = 1,8 % of Metal = (1,8 x 11 kg)/100 = 0,2 kg
- **Electric-electronic waste =** 1,7 kg

Total avoided GHG and energy values are calculated by multiplying the avoided GHG and energy values in Table 28 by the amount of each recyclable, which is determined through inventory analysis. Based on this calculation, it is found that 187 kg CO_2 eq of GHG and 1.404,7 kWh (5.502,82 MJ) of energy are saved as a result of recycling a total of 297,7 kg of recyclable waste (Table 28).

Table 28. Avoided GHG and Energy of Total Recyclable Waste in 1 Mg of MSW

Recycled Materials (297,7 kg)	Avoided GHG (kg CO_2 eq)	Avoided Energy (MJ)
Glass	(0,415 x 37,1 kg) = 15,4	(3,4 x 37,1 kg) = 126,14
PET	(0,81 x 12,7 kg) = 10,16	(27 x 12,7 kg) = 342,9
Plastic	(0,78 x 118,4 kg) = 92,35	(23,2 x 118,4 kg) = 2746,88
Paper-Card.	(0,16 x 116,8 kg) = 18,69	(10,8 x 116,8 kg) = 1261,44
Fe-Metals	(0,494 x 6,48 kg) = 3,2	(5,7 x 6,48 kg) = 36,94
Al-Metals	(10,868 x 4,32 kg) = 46,95	(124,578 x 4,32 kg) = 538,18
Copper	(1,175 x 0,2 kg) = 0,23	(1,699 x 0,2 kg) = 0,34
WEEE	0	0
Total	**187 kg CO_2 eq**	**5.502,82 MJ = 1.404,7 kWh**

5.3.2. Landfill: GHG and Avoided Products

Landfills are a major source of CH_4 emissions, while WTE, coal, natural gas, and oil are important sources of CO_2 fossil emissions. GHG emissions from the landfill process are caused by CH_4 emissions from landfilling, CO_2, and CH_4 emissions from LFG combustion, as well as CO_2 emissions from transportation. In this section, the GHG production and avoided products are caused solely by the combustion of LFG are calculated using stoichiometric calculation.

Landfill GHG and Avoided Products

- **$GHG_{(LFG)}$ =** $GHG_{(CH4)} + GHG_{(Diesel\text{-}oil)}$

  = ($CH_{4(Atmosphere)}$ x $CH_{4(GWP\ 100)}$) + (Diesel consumption x $GWP_{(Diesel\text{-}oil)}$)

  = (32,4 kg CH_4 x 28 kg CO_2 eq/kg CH_4) + (0,53 L x 2,68 kg CO_2 eq/L)

  = 907,2 kg CH_4 + 1,42 kg CH_4 **=** 908,6 kg CO_2 eq
- **Avoided energy =** 92,2 kWh Electrical energy

$CH_{4(GWP\ 100)}$ = 28 kg CO_2 eq /kg CH_4 **$GWP_{(Diesel\text{-}oil)}$** = 2,68 kg CO_2 eq /L Diesel-oil

5.3.3. Composting: GHG and Avoided Products

GHG emissions from composting result from the transportation of compostable materials to composting facilities and the mechanical turning of the compost piles. When organic materials are composted, the anaerobic decomposition of materials produces CH_4. Although composting may result in some production of CH_4 (due to anaerobic decomposition in the centre of the compost pile), compost researchers believe that the CH_4 almost always oxidizes to CO_2 before it escapes from the compost pile. Because the CO_2 emissions from composting are biogenic, well-managed compost piles are not believed to produce CH_4 (USEPA, 2006).

Fuel is used for the operation of windrow turners, materials loading, and transportation, while electricity is consumed in the operation of the machinery. Total energy requirements for in-vessel composting facilities are determined as 55 kWh per tonne of feedstock, while fuel consumption is defined as 3 kWh (0,3 litre of diesel) and 40 kWh of power consumption per Mg of organic waste (EPEM, 2020).

In this thesis, the total primary energy demand is accepted as 190 MJ/Mg (138 MJ as diesel energy and 52 MJ of electrical energy), and GHG emission for the open composting plant (side turner) is accepted as 69,9 kg CO_2 eq per Mg of biowaste input, based on Springer (2011).

The potential of substitution realized by using compost as organic fertilizer is the savings in mineral fertilizers and GHG emissions avoidance. Substitution effects on energy and GHG emission by using 1 Mg of finished compost as a fertilizer are 680 MJ of energy saving and 52,6 kg CO_2 eq avoidance (Springer, 2011). The substitution potential values are obtained from this literature, and substitution effects on energy and GHG are calculated as 680 MJ and 52,6 kg CO_2 eq per Mg of compost used as fertilizer.

Composting GHG and Avoided Products

- **GHG $_{\text{(Composting)}}$ =** 69,9 kg CO_2 eq/Mg
- **Avoided energy = (**Amount of compost using as fertilizer x 0**,**68 MJ/kg)

  = (258,4 kg x 680 MJ)/1.000 kg = 175,7 MJ = 48,84 kWh
- **Avoided GHG =** (Amount of compost using as fertilizer x 52,6 x 10^{-3} kg CO_2 eq)

  = (258,4 kg x 52,6 kg CO_2 eq/kg)/1.000 kg =13,6 kg CO_2 eq

5.3.4. Anaerobic Digestion: GHG and Avoided Products

The main objective of the biogas industry is the reduction of fossil fuel consumption, with the final goal of mitigating the global warming effect. However, anaerobic digestion is associated with the production of several greenhouse gases, namely carbon dioxide, methane, and nitrous oxide. As a consequence, dedicated measures should be taken to reduce these emissions (Paolini et. al., 2018).

In the inventory analysis of this section, the amount of GHG emission is equal to the GHG effect of CH_4 in the biogas that is emitted into the atmosphere. The amounts of CO_2 in the content of biogas and CO_2 emission from biogas combustion are not considered in the GHG calculation due to their biogenic origin.

Anaerobic Digestion GHG and Avoided Products

Biogas to Atmosphere (3 m^3)

$\mathbf{CH_4(Atmosphere)}$ = 0,54 x Biogas to energy = 0,54 x 3 m^3 = 1,62 m^3

$\mathbf{m_{CH4(Atmosphere)}} = d_{(CH4)} \times V_{(CH4)} = 0{,}71\ kg/m^3 \times 1{,}62\ m^3 = 1{,}15\ kg$

- $\mathbf{GHG_{(AD)}} = GHG_{(CH4)} + GHG_{(Diesel\text{-}oil)}$

$= (CH_{4(Atmosphere)} \times CH_{4(GWP\ 100)}) + (\text{Diesel consumption} \times GWP_{(Diesel\text{-}oil)})$

$= (1{,}15\ kg\ CH_4 \times 28\ kg\ CO_2\ eq/kg\ CH_4) + (0{,}9\ L \times 2{,}68\ kg\ CO_2\ eq/L) = 34{,}6\ kg\ CO_2\ eq$

$\mathbf{d_{(CH4)}} = 0{,}71\ kg/m^3$

$\mathbf{CH_{4(GWP\ 100)}} = 28\ kg\ CO_2\ eq$ $\mathbf{GWP_{(Diesel\text{-}oil)}} = 2{,}68\ kg\ CO_2\ eq$ /L Diesel-oil

After the centrifugation process, 670 kg of digestate is centrifuged to separate the solid and liquid parts, resulting in 402 kg digestate containing 25% solids and 268 kg of liquid digestate are obtained. The 402 kg digestate is sent to the composting process to obtained fertilizer products, while the liquid digestate is used directly as fertilizer. Consequently, a total of 525 kg of fertilizer, including 257 kg of compost, is obtained after the composting process, along with 268 kg of liquid digestate from the initial 670 kg of digestate (Fig. 30). By using 525 kg of fertilizer in the anaerobic digestion process, 99,25 kWh of energy and 27,6 kg CO_2 eq GHG are saved.

Digestate Using as Fertilizer:

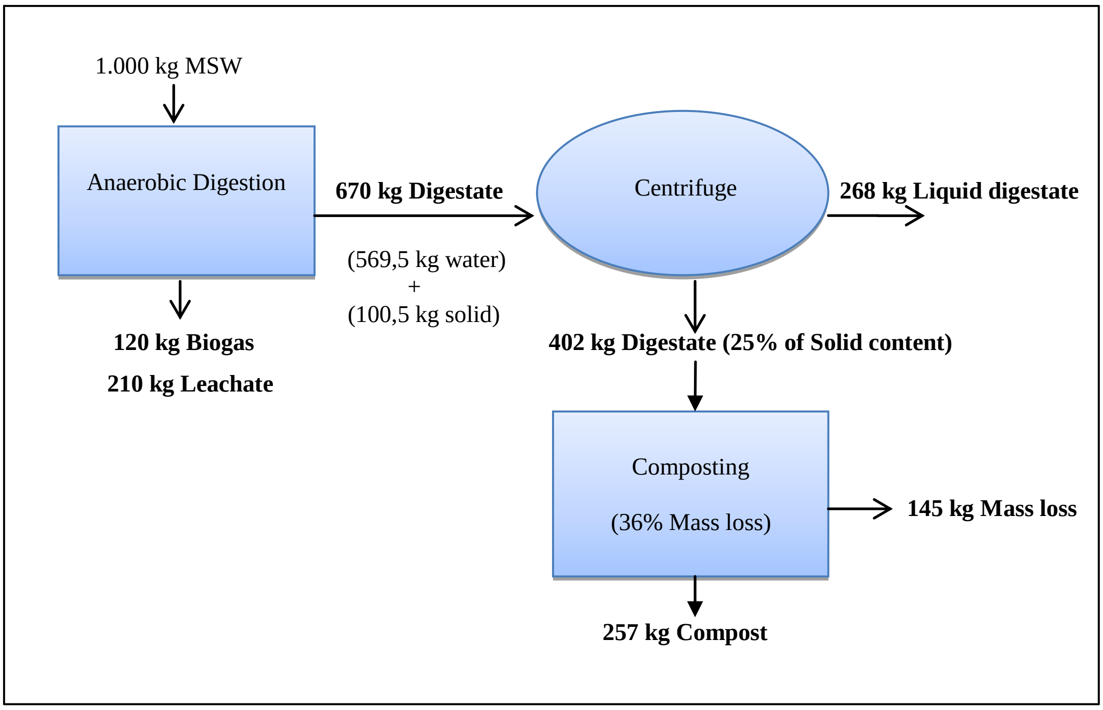

Figure 30. Digestate Using as Fertilizer (Mass Flow)

Fertilizer from Digestate and Avoided Products

670 kg Digestate:

Water content (85%) = (0,85 x Amount of digestate) = 0,85 x 670 kg = 569,5 kg

Solid content (15%) = (0,15 x Amount of digestate) = 0,15 x 670 kg = 100,5 kg

- **Composting input =** (Solid content of digestate x 100)/25 = (100,5 kg x 100)/25 = 402 kg
- **Compost =** Composting input – (Composting input x 0,36) = 402 kg – (402 kg x 0,36) = 257 kg
- **Liquid digestate** = Digestate - Composting input = 670 kg – 402 kg = 268 kg
- **Total fertilizer** = Compost + Liquid digestate = 257 kg + 268 kg **=** 525 kg
- **Avoided energy = (**Amount of compost using as fertilizer x 0**,**68 MJ/kg)

  = (525 kg x 680 MJ)/1000 kg = 357 MJ = 99,25 kWh
- **Avoided GHG =** (Amount of compost using as fertilizer x 52,6.10^{-3} kg CO_2 eq)

  = (525 kg x 52,6 kg CO_2 eq)/1000 kg = 27,6 kg CO_2 eq

5.3.5. Incineration GHG and Avoided Products

GHG emissions caused by the incineration of MSW are CO_2 (carbon dioxide), as well as N_2O (nitrous oxide), NOx (oxides of nitrogen), NH_3 (ammonia), and organic carbon. CH_4 (methane) is not generated in waste incineration during normal operation. It only arises in exceptional cases and to a small extent (from waste remaining in the waste bunker). Thus, in quantitative terms, CH_4 is not considered climate-relevant. The climate-relevant CO_2 emissions from waste incineration are determined by the proportion of waste whose carbon compounds are assumed to be of fossil origin. These emissions are usually defined by combining three waste categories: plastics, textiles, and a combined category for rubber and leather (Johnke, 1999).

According to stoichiometric calculation in the incineration mass and energy balance, 1.725 kg CO_2 is formed from 470 kg C (1 Mg of MSW). Kitchen waste, park and garden waste, paper, and cardboard waste contents, whose carbon compounds are assumed to be of biogenic origin, are calculated to be approximately 64% of the total waste based on MSW characterization data from Istanbul.

In line with this calculation, the amounts of biogenic and fossil carbon are accepted as 64% and 36% of the amount of total carbon content of the waste, respectively. The total amount of CO_2 released by the combustion of 1 Mg of MSW is calculated as 308 kg of CO_2 (fossil) and 547,4 kg of CO_2 (biogenic).

Incineration GHG Emissions

Total CO_2 in 1 Mg MSW: 855,4 kg

- **CO_2 (Biogenic) =** Total CO_2 x 0,64 = 855,4 kg x 0,64 = 547,4 kg
- **CO_2 (Fossil) =** Total CO_2 x 0,36 = 855,4 kg x 0,36 = 308 kg
- **GHG (Incineration) =** $CO_{2\,(Fossil)}$ = 308 kg CO_2 eq

5.4. Development of Municipal Solid Waste Management (MSWM) Scenarios

In this thesis, MSWM scenarios are created under two categories as basic scenarios and combination scenarios, which are composed of different percentages of the landfill, recycling, composting, anaerobic digestion, and incineration processes. These scenarios are analysed in terms of climate change, ecosystem quality, and human health.

Collected waste fractions (Cw_i), sorted waste fractions (Sr_i), and residual waste fractions (Rw_i) are calculated separately for each scenario with the following equations (Eq. 12, 13 and 14):

Calculation of mass flow diagrams for the lines

Collected waste fraction (Cw_i) $\longrightarrow$ $\mathbf{Cw_i} = Cr_i \times m_i$ **(Eq. 12)**

Sorted waste fraction (Sw_i) $\longrightarrow$ $\mathbf{Sw_i} = Cw_i \times Sr_i$ **(Eq. 13)**

Residual waste fraction (Rw_i) $\longrightarrow$ $\mathbf{Rw_i} = Cw_i \times Wr_i$ **(Eq. 14)**

Cr: Collection rate

i: Waste fractions

Sr: Sorting rate

m_i: Mass of waste fraction

Wr: Residual waste rate

- **Basic Scenario 1:** This scenario represents the worst-case MSWM scenario, where all the mixed collected MSW is assumed to be sent directly to the landfill area (Fig. 31). The aim of this scenario is to examine the results solely based on the disposal of MSW in the landfill.

Landfill $\longrightarrow$ 1.000 kg MSW

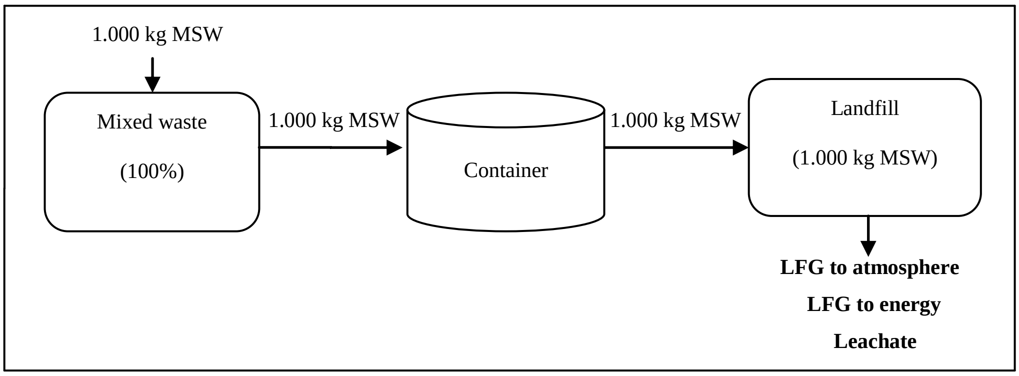

Figure 31. Basic Scenario-1 Mass Flow Diagram

- **Basic Scenario 2:** All the mixed collected MSW is sent to waste incineration plants with energy recovery in this scenario (Fig. 32). The purpose of developing this scenario is to analyse the resulting environmental impacts when MSW is completely treated by incineration.

Incineration ⟶ 1.000 kg MSW

Landfill ⟶ 167,5 kg Bottom ash

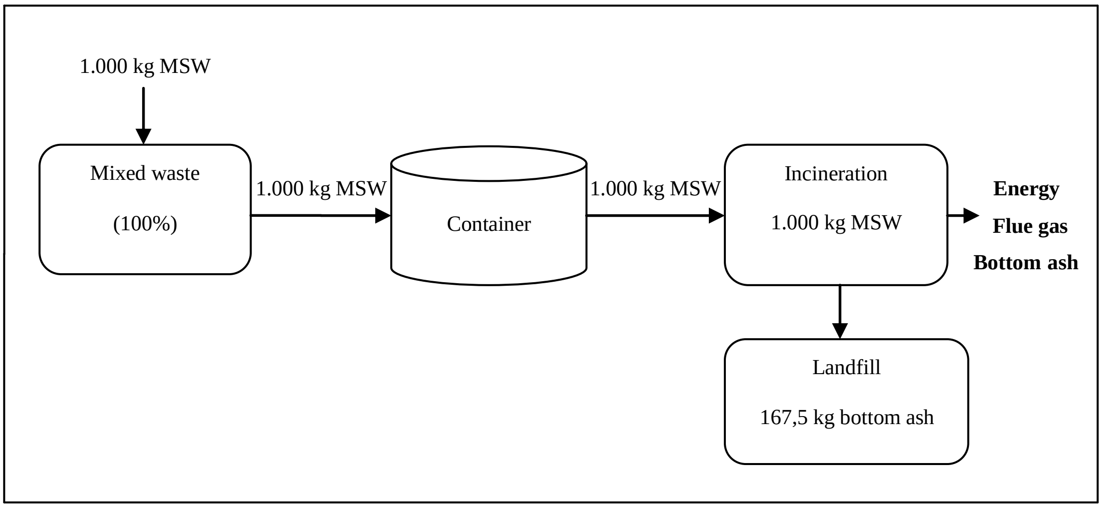

Figure 32. Basic Scenario-2 Mass Flow Diagram

The collection rate (Cr) and sorting rate (Sr) of biowaste and dry recyclable waste are zero because there is no source separation/collection. Cr and Wr of residual waste are both “1” (100%) because all the waste is collected as residual waste without any source separation in B.S-1 and B.S-2 (Table 29).

Table 29. Cr, Sr and Wr of Basic Scenario-1 and Basic Scenario-2

Fractions	Biowaste Line			Dry Recyclable Waste Line			Residual Waste Line		
	Cr	Sr	Wr	Cr	Sr	Wr	Cr	Sr	Wr
Biowaste	0	0	1	0	0	1	1	0	1
Paper	0	0	1	0	0	1	1	0	1
Glass	0	0	1	0	0	1	1	0	1
Plastic	0	0	1	0	0	1	1	0	1
Metal	0	0	1	0	0	1	1	0	1
Electric-Electronic	0	0	1	0	0	1	1	0	1
Hazardous Waste	0	0	1	0	0	1	1	0	1
Textile	0	0	1	0	0	1	1	0	1
Nappy-Diaper	0	0	1	0	0	1	1	0	1
Other Combustible	0	0	1	0	0	1	1	0	1
Other Non Combustible	0	0	1	0	0	1	1	0	1

- **Basic Scenario 3:** It is assumed that 9,9 kg of metal is collected at a 90% collection rate, and 9,4 kg of metal is sent to the recycling process with a 95% sorting rate (Table 30). Before the waste is sent to the incineration plant with energy recovery, 1 Mg of the waste is separated for recovery, and the residue (155,7 kg bottom ash) arising from the incineration plant is sent to the landfill area (Fig. 33). This scenario is almost the same as the previous one, the only difference being the recycling of metals.

Recycling ⟶ 9,4 kg Metal

Incineration ⟶ 990,6 kg MSW

Landfill ⟶ 166 kg Bottom ash

Table 30. Cr, Sr and Wr of Basic Scenario-3

Fractions	Biowaste Line			Dry Recyclable Waste Line			Residual Waste Line		
	Cr	Sr	Wr	Cr	Sr	Wr	Cr	Sr	Wr
Organic Waste	0	0	1	0	0	1	1	0	1
Paper	0	0	1	0	0	1	1	0	1
Glass	0	0	1	0	0	1	1	0	1
Plastic	0	0	1	0	0	1	1	0	1
Metal	0	0	1	0,9	0,95	0,05	0,1	0	1
Electric-Electronic	0	0	1	0	0	1	1	0	1
Hazardous Waste	0	0	1	0	0	1	1	0	1
Textile	0	0	1	0	0	1	1	0	1
Nappy-Diaper	0	0	1	0	0	1	1	0	1
Other Combustible	0	0	1	0	0	1	1	0	1
Other Non Combustible	0	0	1	0	0	1	1	0	1

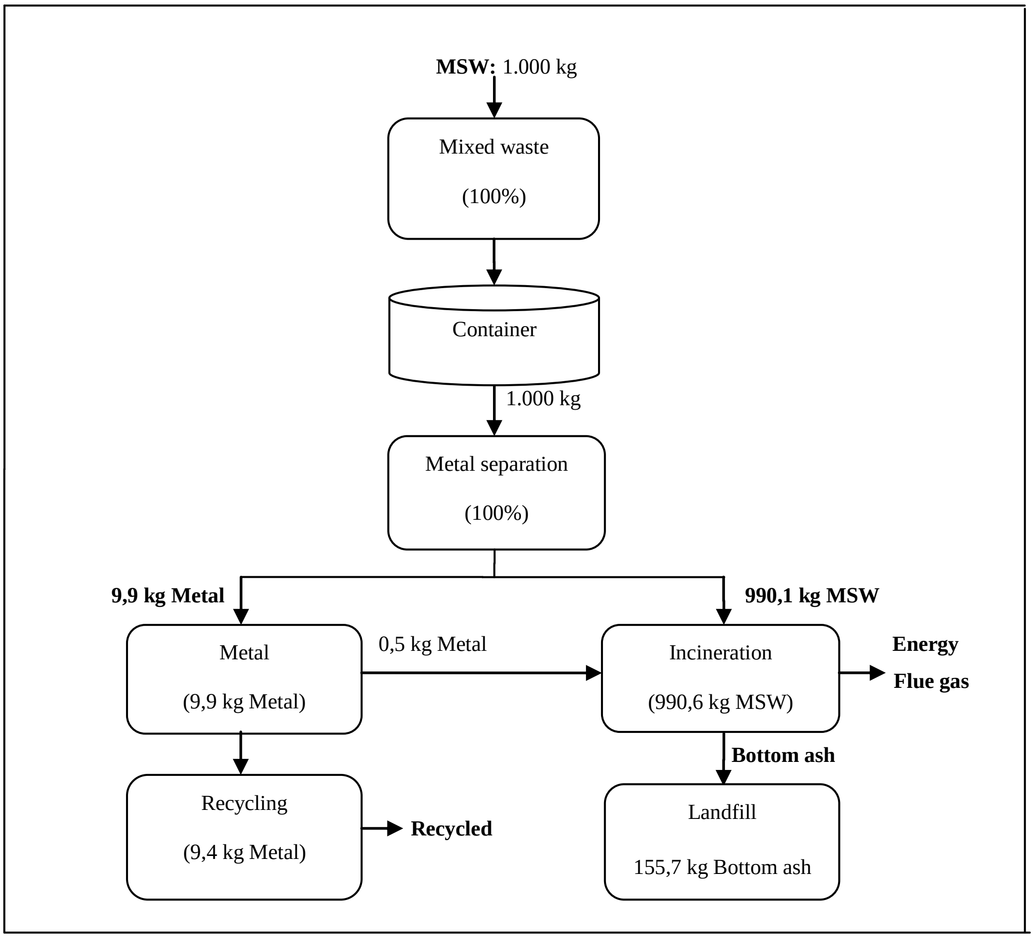

Figure 33. Basic Scenario-3 Mass Flow Diagram

• **Basic Scenario 4 (a):** All the MSW is separated as dry and wet waste at its source. This scenario aims to analyse the results arising when the recoverable waste is collected separately as dry and wet waste, while impurities and residues from recoverable waste (biowaste and recyclable dry waste) and non-recoverable waste are sent to the landfill area. Of the total biowaste (515,8 kg), 75% is accepted, resulting in the collection of 386,9 kg of biowaste. Out of the collected biowaste, 80% (309,4 kg) is sent to the composting and anaerobic digestion processes, while the residues from compost preparation and the collected impurities (157,6 kg) are sent to the landfill. Half of the remaining biowaste (154,7 kg) is directed to the composting process. Approximately 85,7% of the recyclable waste (297,7 kg) is collected, amounting to 255 kg. Out of the collected recyclable waste, 72,3% (184,5 kg) is recycled, while the remaining 506,1 kg of residual waste is sent to the landfill process (Fig. 34).

Composting → 154,7 kg Biowaste
Anaerobic Digestion → 154,7 kg Biowaste
} 309,4 kg Biowaste (60% of 515,8 kg Total biowaste)
Recycling → 184,5 kg Recyclable dry waste → (62 % of 297,7 kg Recyclable)
Landfill → 506,1 kg Residual waste

• **Basic Scenario 4 (b):** This scenario is almost the same as Basic Scenario-4(a), except for the residue disposal method. The amount of residue arising from the disposal processes is sent to the incineration process with energy recovery instead of the landfill (Fig. 35).

Composting → 154,7 kg Biowaste
Anaerobic Digestion → 154,7 kg Biowaste
} 309,4 kg Biowaste (60% of 515,8 kg Total biowaste)
Recycling → 184,5 kg Recyclable dry waste → (62 % of 297,7 kg Recyclable)
Incineration → 506,1 kg Residual waste

Cr, Sr, and Wr of Basic Scenario-4(a) and Basic Scenario-4(b) are the same for each waste category in the biowaste, dry recyclable waste, and residual waste lines (Table 31).

Table 31. Cr, Sr and Wr of Basic Scenario-4(a) and Basic Scenario-4(b)

Fractions	Biowaste Line			Dry Recyclable Waste Line			Residual Waste Line		
	Cr	Sr	Wr	Cr	Sr	Wr	Cr	Sr	Wr
Biowaste	0,75	0,8	0,2	0,25	0	1,0	0	0	0
Paper	0,1	0	1	0,9	0,7	0,3	0	0	0
Glass	0,1	0	1	0,9	0,8	0,2	0	0	0
Plastic	0,2	0	1	0,8	0,7	0,3	0	0	0
Metal	0,1	0	1	0,9	0,95	0,05	0	0	0
Electric-Electronic	0	0	1	1	0,8	0,2	0	0	0
Hazardous Waste	0	0	1	1	0	1	0	0	0
Textile	0	0	1	1	0	1	0	0	0
Nappy-Diaper	0,5	0	1	0,5	0	1	0	0	0
Other Combustible	0,1	0	1	0,9	0	1	0	0	0
Other Non Combustible	0,5	0	1	0,5	0	1	0	0	0

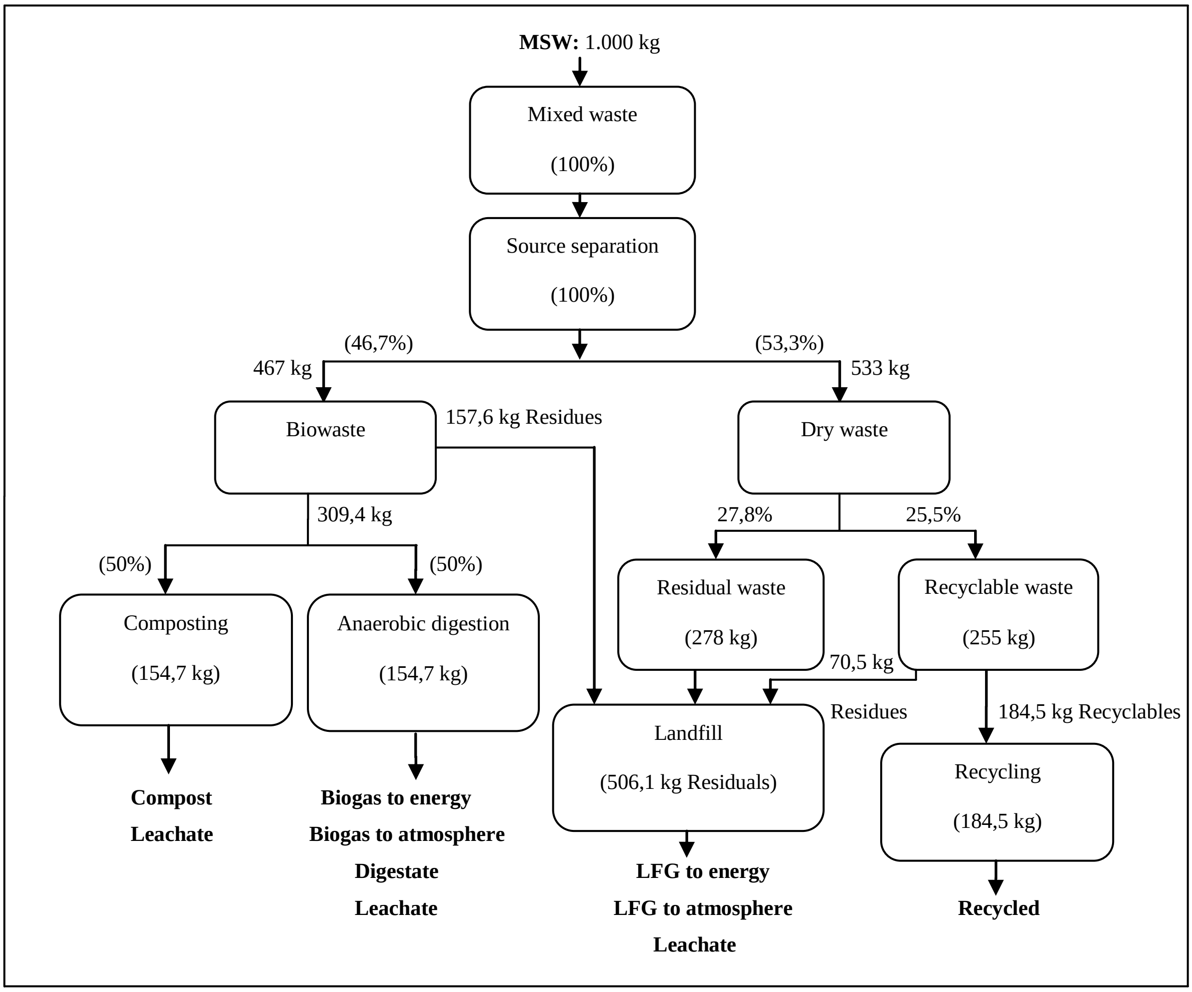

Figure 34. Basic Scenario-4(a) Mass Flow Diagram

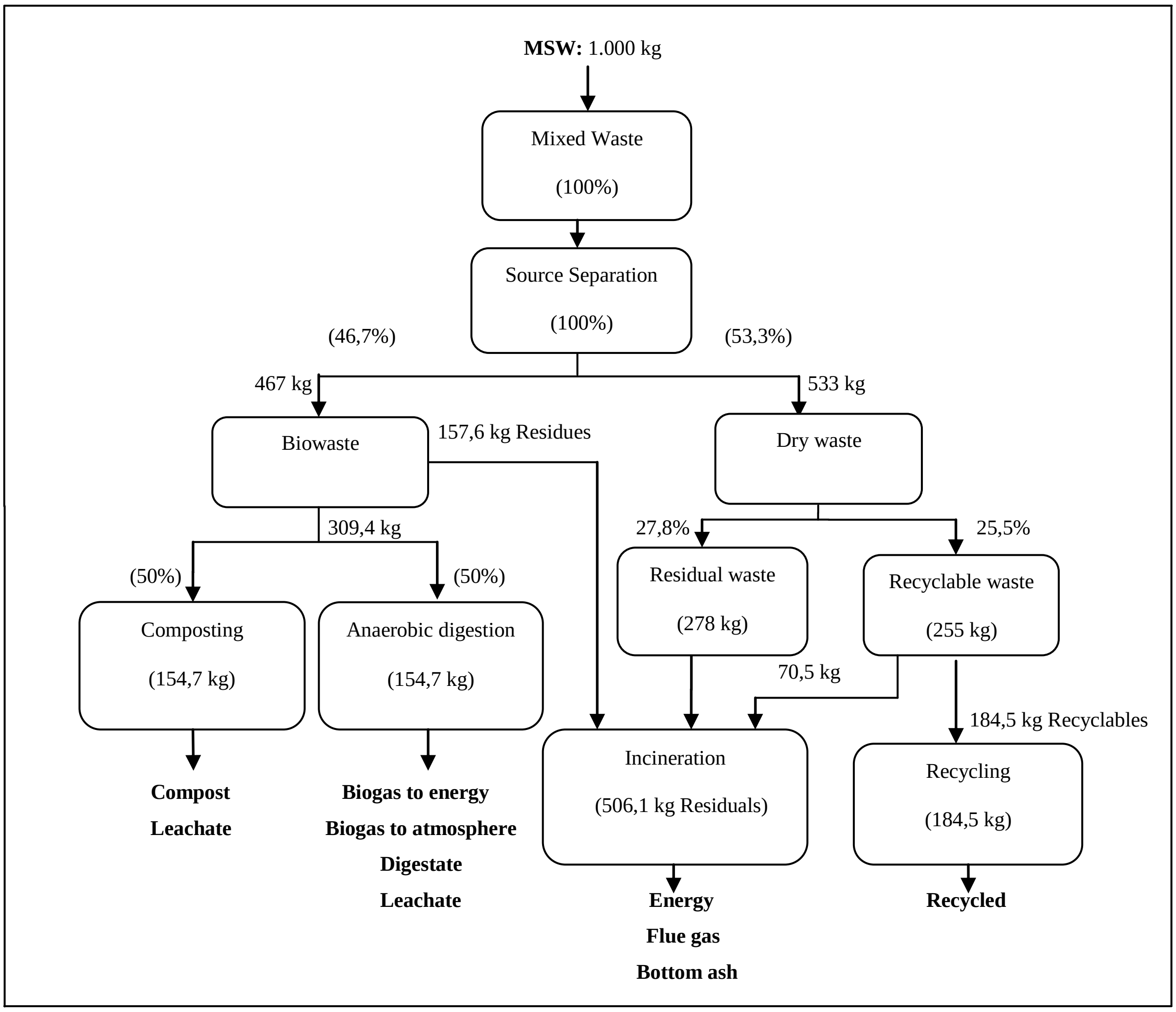

Figure 35. Basic Scenario-4(b) Mass Flow Diagram

• Basic Scenario 5 (a) (EU Targets-2030):

It aims to achieve the recycling and landfill targets of EU for 2030 with this scenario. According to the Waste Framework Directive, the recycling rate should be at least 65% in 2035, and only 10% of the mixed waste must be sent to the landfill area without going through any disposal process. For this purpose, this scenario assumes that approximately 75% of the biowaste (386,9 kg) is collected separately, and 95% of the collected biowaste (367,5 kg) is sorted and sent to the composting process, while the remaining 5% of the collected biowaste (19,4 kg) and the impurities in the collected biowaste (20,5 kg) are sent to the incineration process as residues. On the other hand, 265,9 kg of the recyclable waste (88,7% of the total 297,7 kg of recyclable waste) is collected separately, and 79,5% of the collected recyclable waste is sent to the recycling process, while 20,5% of the residue is disposed of through the incineration process. Apart from these, 100 kg of the 326,7 kg of residual waste is disposed of in landfill areas, while 226,7 kg of the residual waste is incinerated with energy recovery along with the residues arising from biowaste and recycling waste. In this scenario, only 10% of the residual waste (100 kg) is sent to the landfill area (Figure 36).

Composting → 367,5 kg Biowaste (71,25% of 515,8 kg Total biowaste)

Recycling → 211,5 kg Recyclable waste (71,45% of 296 kg Total recyclable)

Landfill → 100 kg Residual waste

Incineration → 321 kg Residual waste

Cr, Sr, and Wr of Basic Scenario-5(a) and Basic Scenario-5(b) are the same for each of the waste categories in the biowaste, dry recyclable waste, and residual waste lines (Table 32).

Table 32. Cr, Sr and Wr of Basic Scenario-5(a) and Basic Scenario-5(b)

Fractions	Biowaste Line			Dry Recyclable Waste Line			Residual Waste Line		
	Cr	**Sr**	**Wr**	**Cr**	**Sr**	**Wr**	**Cr**	**Sr**	**Wr**
Biowaste	0,75	0,95	0,05	0,05	0	1,0	0,2	0	1
Paper	0,05	0	1	0,9	0.95	0,05	0,05	0	1
Glass	0,05	0	1	0,8	0,95	0,05	0,15	0	1
Plastic	0,07	0	1	0,7	0,8	0,2	0,23	0	1
Metal	0,05	0	1	0,85	0,95	0,05	0,1	0	1
Electric-Electronic	0	0	1	0,7	0,95	0,05	0,3	0	1
Hazardous Waste	0	0	1	0	0	1	1	0	1
Textile	0	0	1	0	0	1	1	0	1
Nappy-Diaper	0	0	1	0	0	1	1	0	1
Other Combustible	0,05	0	1	0,05	0	1	0,9	0	1
Other Non Combustible	0	0	1	0	0	1	1	0	1

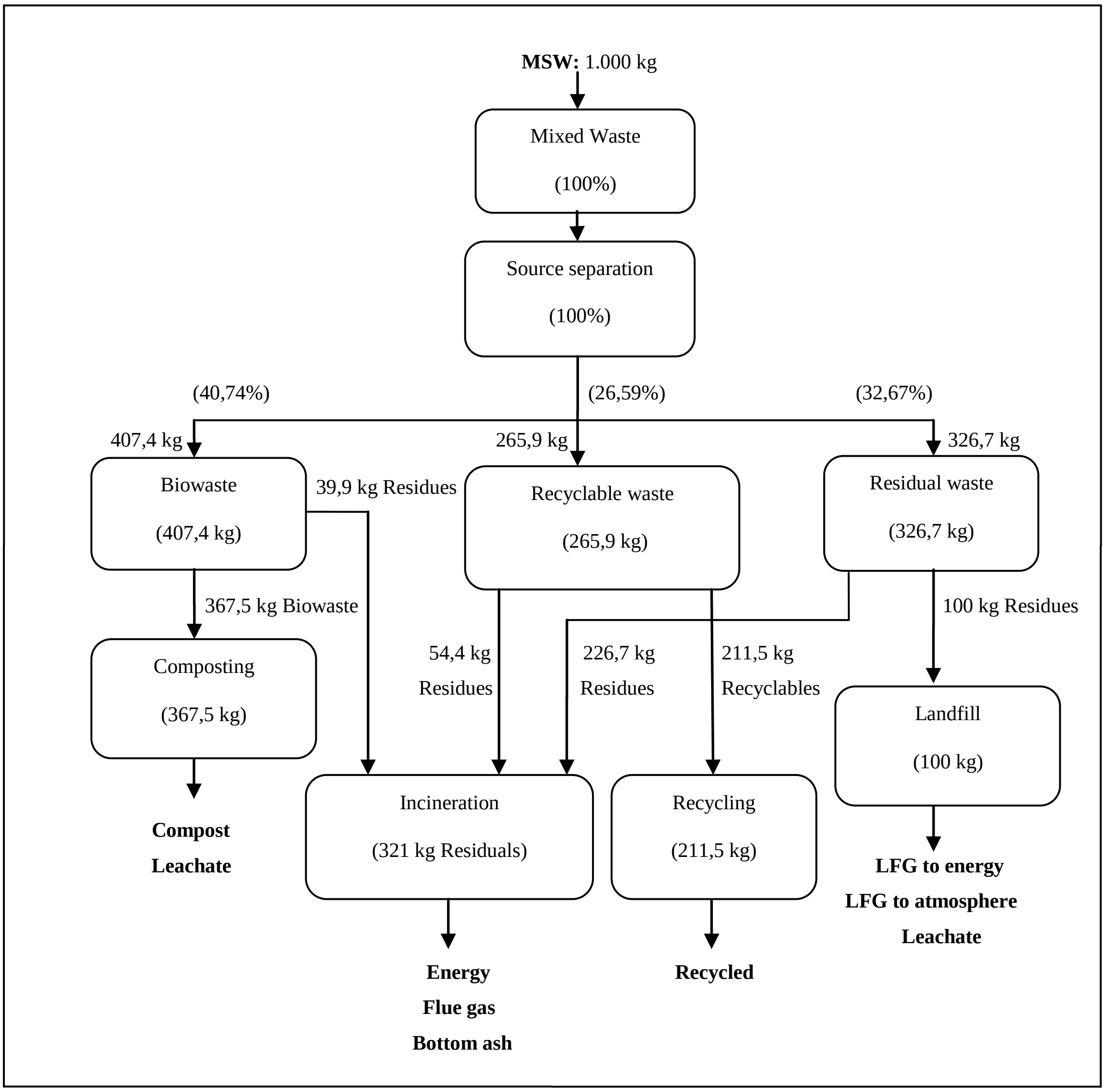

Figure 36. Basic Scenario-5(a) Mass Flow Diagram

• **Basic Scenario 5 (b):** This scenario is almost the same as the Basic Scenario-5(a), except for the biological treatment. The biowaste is sent to the anaerobic digestion process instead of composting (Fig. 37).

Anaerobic Digestion ⟶ 367,5 kg Biowaste (71,25% of 515,8 kg Total biowaste)

Recycling ⟶ 211,5 kg Recyclable waste (71,45% of 296 kg Total recyclables)

Landfill ⟶ 100 kg Residual waste

Incineration ⟶ 321 kg Residual waste

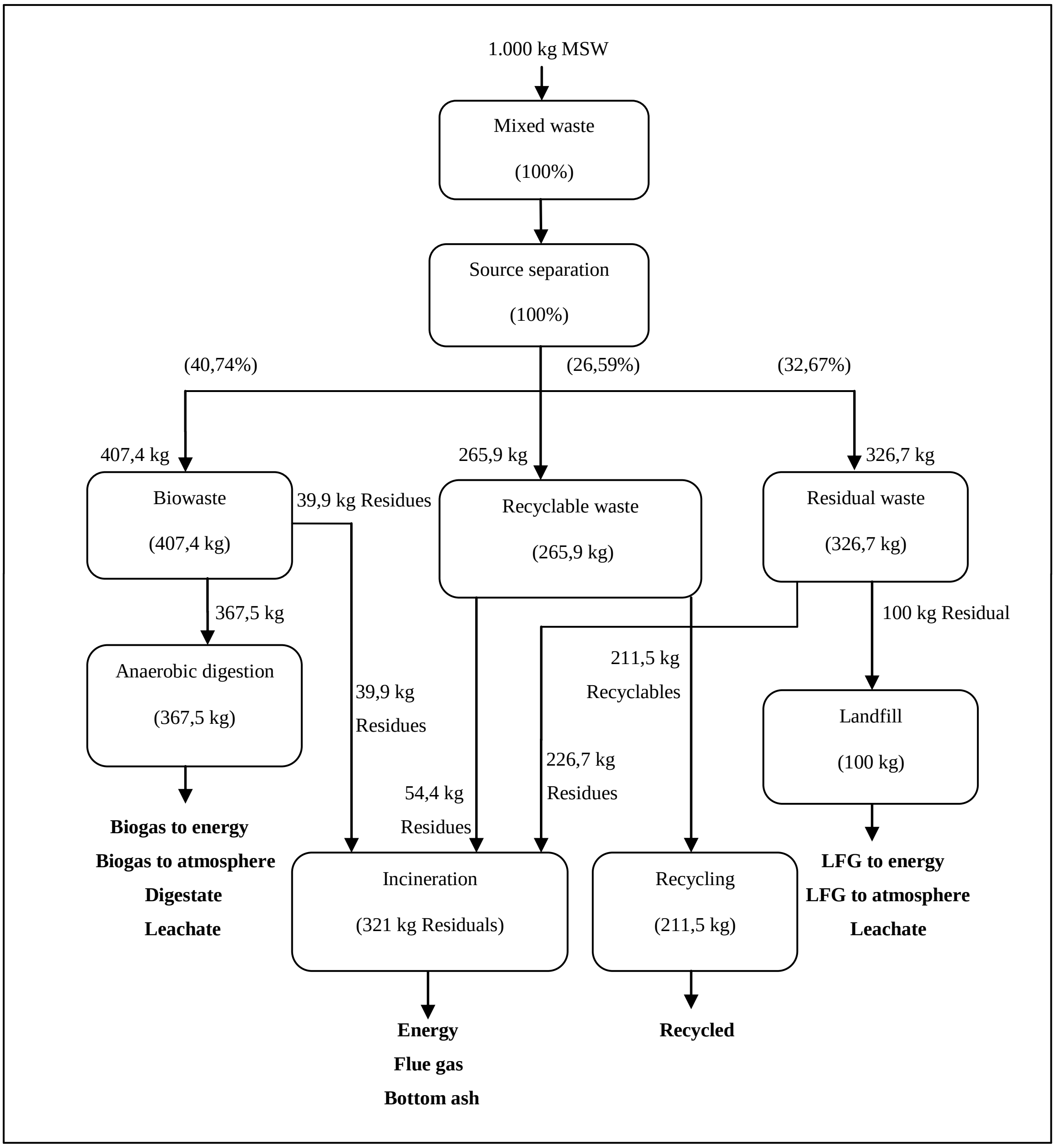

Figure 37. Basic Scenario 5(b) Mass Flow Diagram

- **Combination Scenario 1:** This scenario is developed to demonstrate the current MSWM situation in Istanbul and to analyse its impacts. Currently, 11% of the MSW (1 Mg) collected from parks, gardens, and marketplaces goes directly to the composting process, 6% of the packaging waste (60 kg) collected separately from its source goes for recycling, while a large amount of the mixed waste (830 kg) goes to the landfill site in Istanbul (Fig 38).

Composting ⟶ 110 kg Biowaste

Recycling ⟶ 60 kg Recyclable dry waste

Landfill ⟶ 830 kg Residual waste

Cr, Sr, and Wr of Combination scenario-1 for each of the waste categories are shown in the biowaste, dry recyclable waste, and residual waste lines (Table 33).

Table 33. Cr, Sr and Wr of Combination Scenario-1

Fractions	Biowaste Line			Dry Recyclable Waste Line			Residual Waste Line		
	Cr	**Sr**	**Wr**	**Cr**	**Sr**	**Wr**	**Cr**	**Sr**	**Wr**
Biowaste	0,225	0,95	0,05	0,05	0	1,0	0,725	0	1
Paper	0	0	1	0.3	0,95	0,05	0,7	0	1
Glass	0	0	1	0,1	0,95	0,05	0,9	0	1
Plastic	0	0	1	0,2	0,8	0,2	0,8	0	1
Metal	0	0	1	0,1	0,95	0,05	0,9	0	1
Electric-Electronic	0	0	1	0,1	0,95	0,05	0,9	0	1
Hazardous Waste	0	0	1	0	0	1	1	0	1
Textile	0	0	1	0	0	1	1	0	1
Nappy-Diaper	0	0	1	0	0	1	1	0	1
Other Combustible	0	0	1	0,05	0	1	0,95	0	1
Other Non Combustible	0	0	1	0	0	1	1	0	1

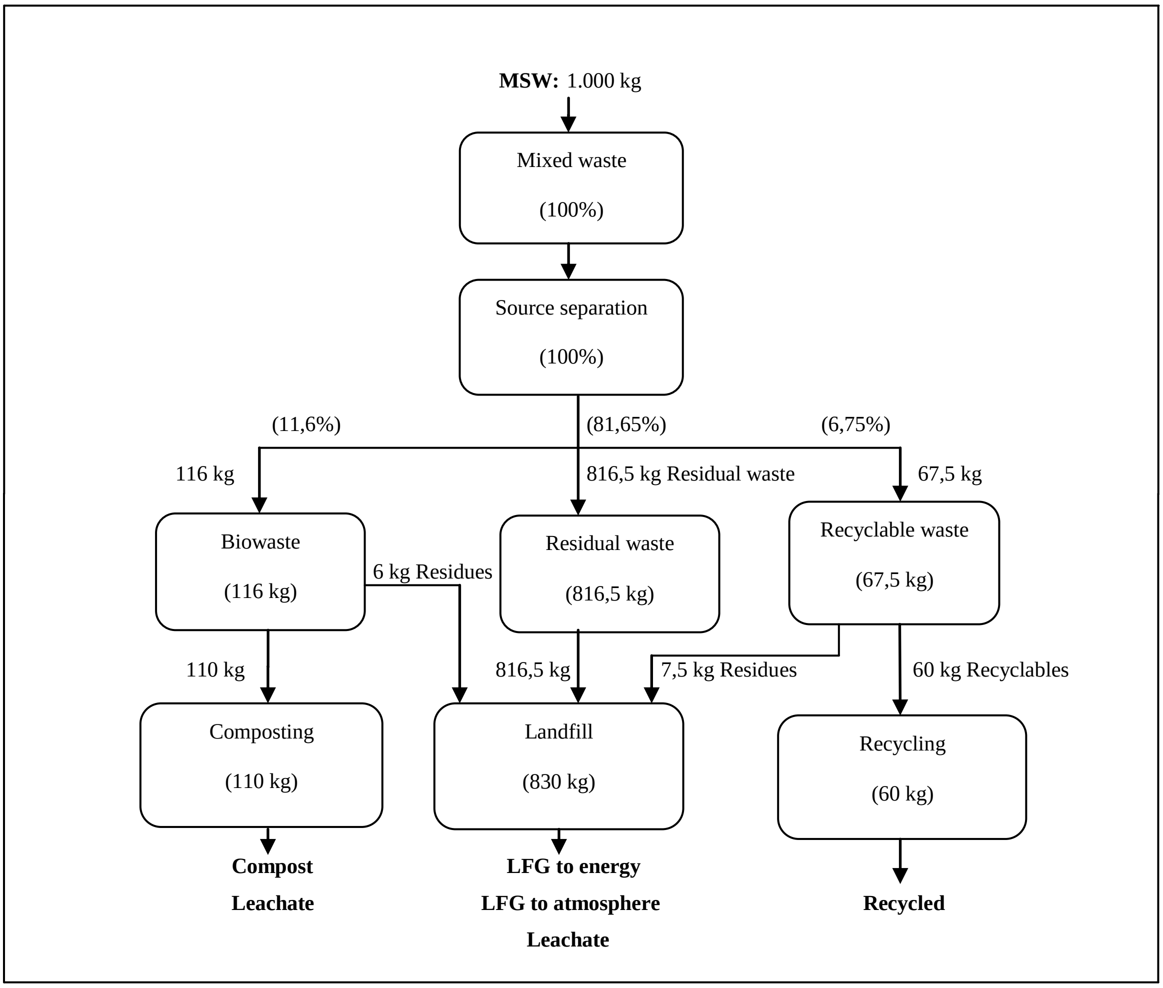

Figure 38. Combination Scenario-1 Mass Flow Diagram

• **Combination Scenario 2: (2023 Targets of Istanbul Metropolitan Municipality):** This scenario aims to achieve the recycling and landfill targets of Istanbul by 2023. According to the MSWM targets received from IMM, approximately 25% of MSW (250 kg) will be disposed of through the incineration process with energy recovery, 25% of MSW (250 kg) will be disposed of through the anaerobic digestion process, approximately 35% of the residual waste (350 kg) will be sent to the landfill area without going through any disposal process, while 15% of MSW will be recycled (Fig. 39).

Anaerobic Digestion → 250 kg Biowaste (48,47% of 515,8 kg Biowaste)

Recycling → 150 kg Recyclable dry waste (50,67% of 296 kg Recyclable waste)

Landfill → 350 kg Residual waste

Incineration → 250 kg Residual waste

Cr, Sr, and Wr of Combination Scenario-2 for each of the waste categories are shown in the biowaste, dry recyclable waste, and residual waste lines (Table 34).

Table 34. Cr, Sr and Wr of Combination Scenario-2

Fractions	Biowaste Line			Dry Recyclable Waste Line			Residual Waste Line		
	Cr	**Sr**	**Wr**	**Cr**	**Sr**	**Wr**	**Cr**	**Sr**	**Wr**
Biowaste	0,51	0,95	0,05	0,05	0	1,0	0.44	0	1
Paper	0	0	1	0,67	0,95	0,05	0,33	0	1
Glass	0	0	1	0,45	0,95	0,05	0,55	0	1
Plastic	0	0	1	0,5	0,8	0,2	0,5	0	1
Metal	0	0	1	0,65	0,95	0,05	0,35	0	1
Electric-Electronic	0	0	1	0,5	0,95	0,05	0,95	0	1
Hazardous Waste	0	0	1	0	0	1	1	0	1
Textile	0	0	1	0	0	1	1	0	1
Nappy-Diaper	0	0	1	0	0	1	1	0	1
Other Combustible	0	0	1	0,05	0	1	0,95	0	1
Other Non Combustible	0	0	1	0	0	1	1	0	1

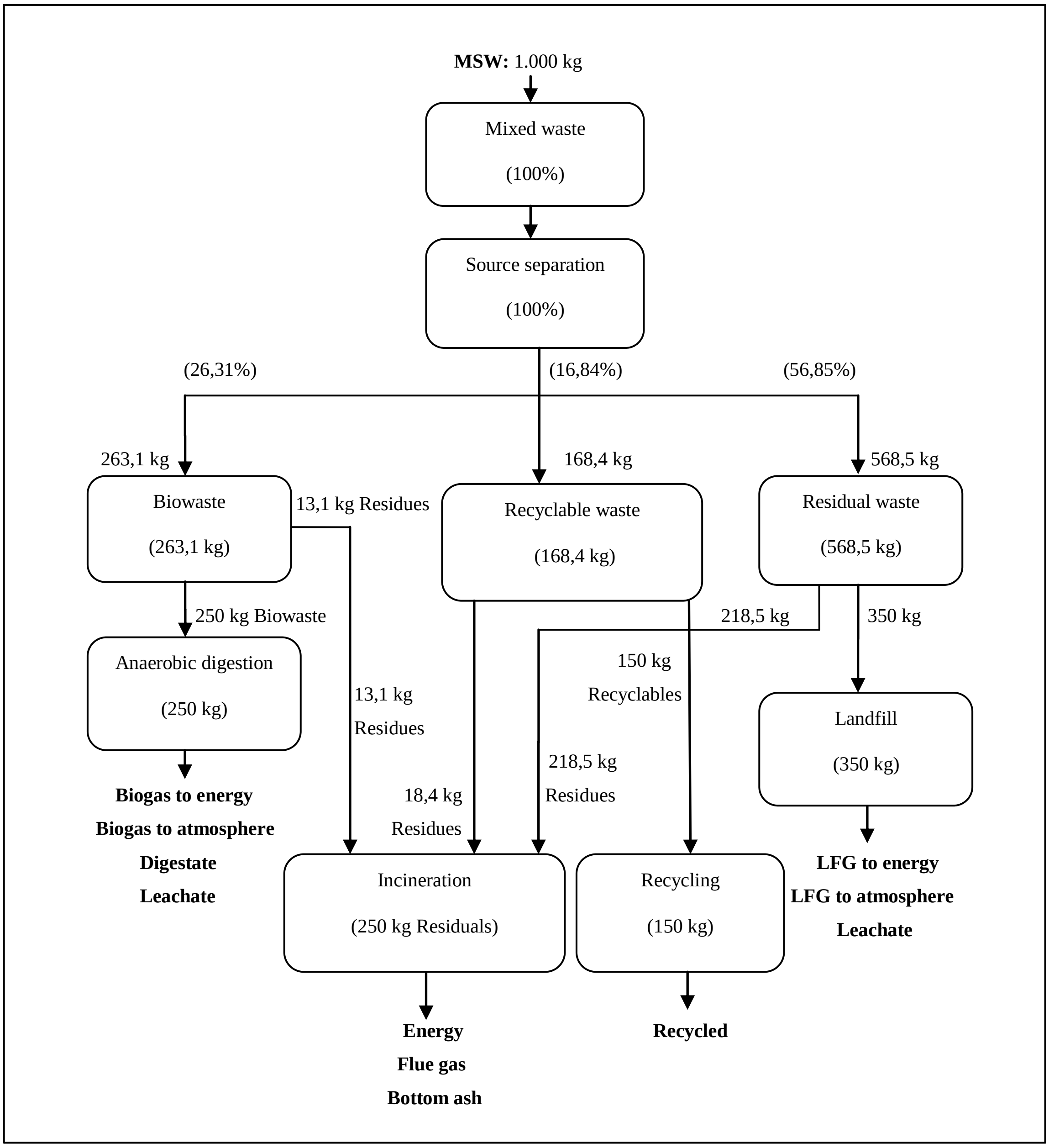

Figure 39. Combination Scenario-2 Mass Flow Diagram

• **Combination Scenario 3 (Transition scenario that is applicable to Istanbul currently):** This scenario is a transition scenario that includes the realistic percentage of solid waste disposal methods applicable to Istanbul to meet 50% of the recycling and landfill targets of the EU by 2030 (Fig 40).

Composting → 132,3 kg Biowaste (25,65% of 515,8 kg Biowaste)

Recycling → 75,3 kg Recyclable Waste (25,44% of 296 kg Recyclable waste)

Landfill → 542,4 kg Residual Waste

Incineration → 250 kg Residual Waste

Cr, Sr, and Wr of Combination Scenario-3 are shown for each of the waste categories in the biowaste, dry recyclable waste, and residual waste lines (Table 35).

Table 35. Cr, Sr and Wr of Combination Scenario-3

Fractions	Biowaste Line			Dry Recyclable Waste Line			Residual Waste Line		
	Cr	Sr	Wr	Cr	Sr	Wr	Cr	Sr	Wr
Biowaste	0,27	0,95	0,05	0,05	0	1,0	0,68	0	1
Paper	0	0	1	0,4	0,95	0,05	0,6	0	1
Glass	0	0	1	0,1	0,95	0,05	0,9	0	1
Plastic	0	0	1	0,2	0,8	0,2	0,8	0	1
Metal	0	0	1	0,1	0,95	0,05	0,9	0	1
Electric-Electronic	0	0	1	0,1	0,95	0,05	0.9	0	1
Hazardous Waste	0	0	1	0	0	1	1	0	1
Textile	0	0	1	0	0	1	1	0	1
Nappy-Diaper	0	0	1	0	0	1	1	0	1
Other Combustible	0	0	1	0,05	0	1	0,95	0	1
Other Non Combustible	0	0	1	0	0	1	1	0	1

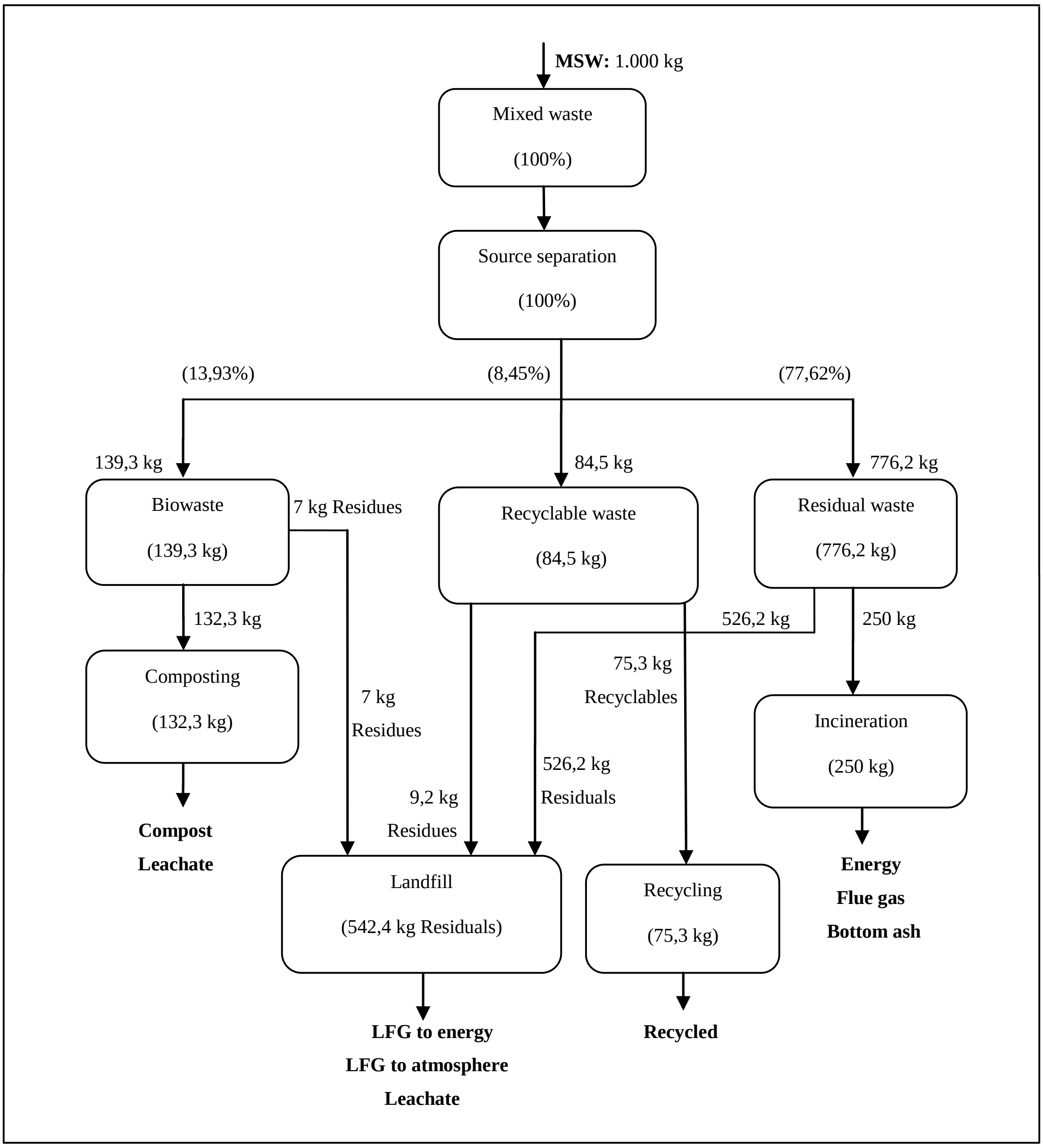

Figure 40. Combination Scenario-3 Flow Diagram

6. RESULT AND DISCUSSIONS

6.1. Mass and Energy Balance Calculation Results

The mass and energy balance results of the scenarios are analysed for “1 Mg” of MSW under two main categories as basic and combination scenarios mass balances.

In the basic and combination scenarios mass balance calculations, leachate and LFG (CH_4 to energy, CH_4 to atmosphere, and CO_2) calculations are performed as output for the landfill process. The amounts of compost, leachate, CO_2, and H_2O are calculated as process output in the composting process. The amounts of biogas (biogas to atmosphere and biogas to energy), digestate, and leachate are calculated as output in the anaerobic digestion process, while the amounts of flue gas, bottom ash, and $H_2O_{(gas)}$ are calculated as incineration process outputs in the mass balance calculations.

6.1.1. Mass Balance Calculation Results

In B.S-1; 1.555 kg of leachate and 54 kg of CH_4 are generated from disposal of 1 Mg of MSW by the landfill process. Based on landfill mass balance calculations in Chapter (5.2.1), energy is obtained by burning 40% of CH_4 (21,6 kg) in LFG, and the remaining 60% of CH_4 (32,4 kg) is released into the atmosphere along with the amount of 149 kg CO_2 (Fig. 41).

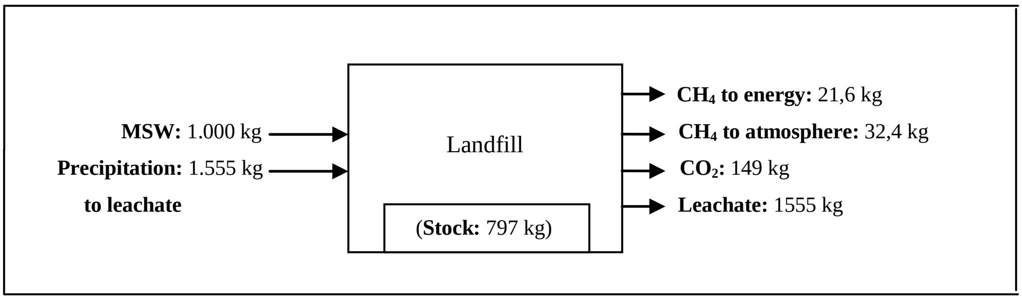

Figure 41. Basic Scenario-1 Mass Balance

In B.S-2; 33,5 kg of water and 5.269 kg of air are required for the incineration of 1000 kg of MSW, while 167,5 kg of bottom ash and 6.135 kg (4.898 m^3) of wet flue gas are formed as output (Fig. 42). The wet flue gas includes 855,4 kg of CO_2, 751 kg of H_2O, 2,6 kg of SO_2, 17,95 kg of NO_X, 2.533 kg of N, and 1.975 kg of the supplied air (l), including evaporated H_2O from the waste.

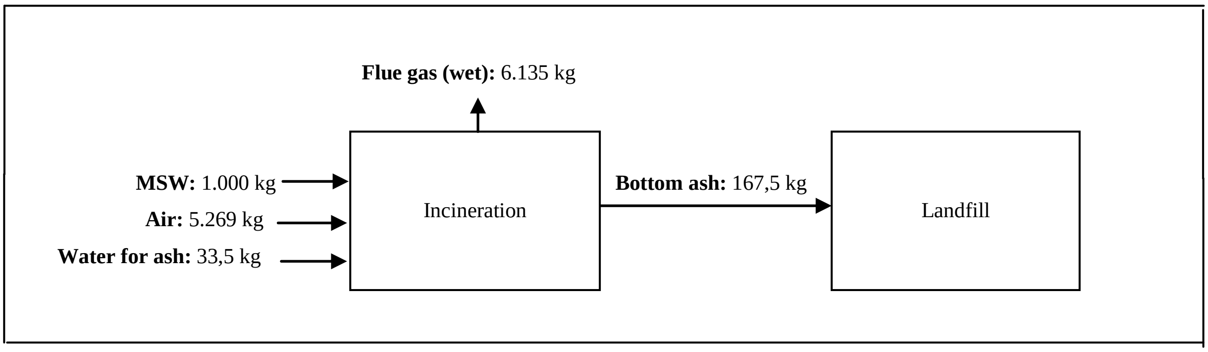

Figure 42. Basic Scenario-2 Mass Balance

After recycling 9,4 kg of metal in the MSW, the remaining 990,6 kg of MSW is disposed of by incineration. 31,1 kg of water for ash and 5.269 kg of air are required for the incineration of 990,6 kg of MSW, while 155,7 kg of bottom ash and 6.135 kg (4.898 m^3) of wet flue gas are formed as output (Fig. 43). The wet flue gas includes 855,4 kg of CO_2, 751 kg of H_2O, 2,6 kg of SO_2, 17,95 kg of NO_X, 2.533 kg of N, 1.975 kg of the supplied air (l).

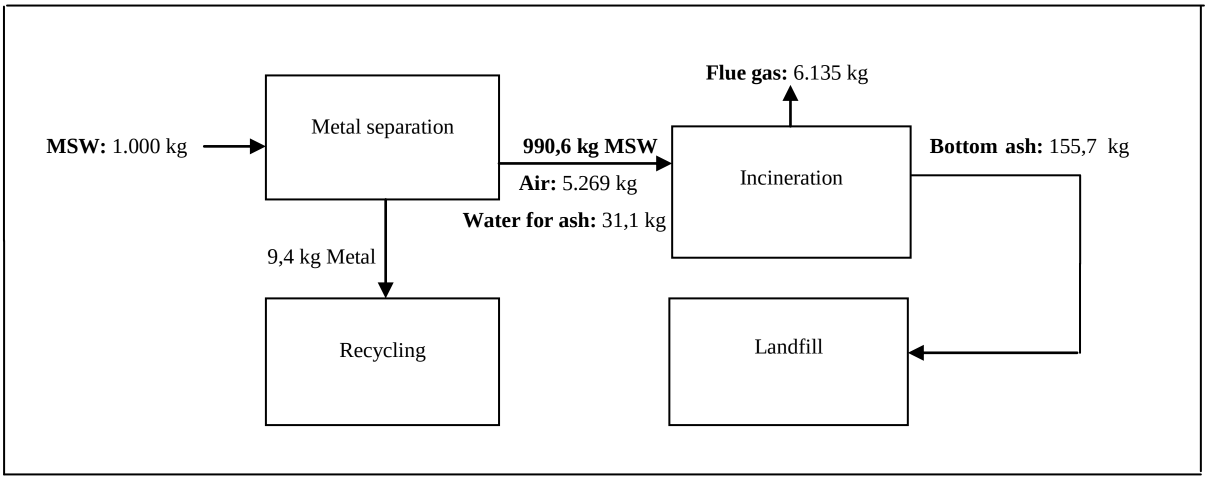

Figure 43. Basic Scenario-3 Mass Balance

B.S-4(a) comprises composting, anaerobic digestion, recycling, and landfill processes. On the one hand, 75,2 kg of compost (40 kg fine compost and 35,2 kg coarse compost), 25 kg of leachate, and 97,8 kg of CO_2 and H_2O $_{(gas)}$ are generated by composting 154,7 kg of biowaste, 18,6 kg of biogas, 103,6 kg of digestate, and 32,5 kg of leachate arises after the anaerobic digestion process. On the other hand, the remaining 506,1 kg of residual waste is sent to the landfill area for disposal 27,3 kg of CH_4, 75,5 kg of CO_2, and 786,9 kg of leachate form as the result of the landfill process (Fig 44). The disposal process and mass balance results of B.S-4(b) are almost the same as B.S-4(a), the only difference is that the incineration process is used instead of the landfill process. 16,9 kg of water for ash and 2.664,6 kg of air are required for the incineration of 506,1 kg of MSW, while 84,7 kg of bottom ash and 3.102,9 kg (2.482 m^3) of wet flue gas are generated (Fig. 45). The wet flue gas includes 433 kg of CO_2, 379,54 kg of H_2O, 1,3 kg of SO_2, 9,08 kg of NO_X, 1.284 kg of N, and 996 kg of the supplied air (l).

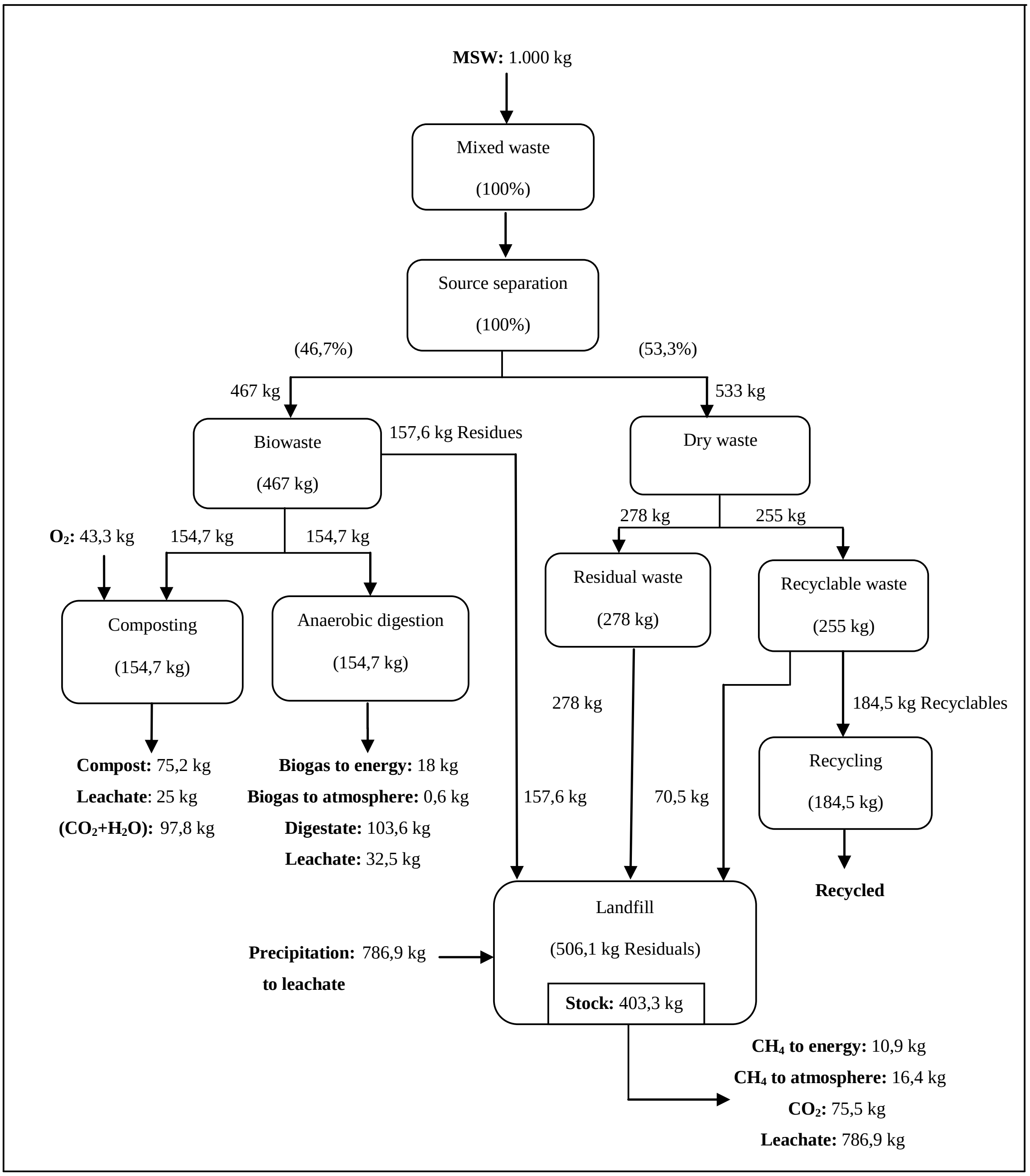

Figure 44. Basic Scenario-4(a) Mass Balance

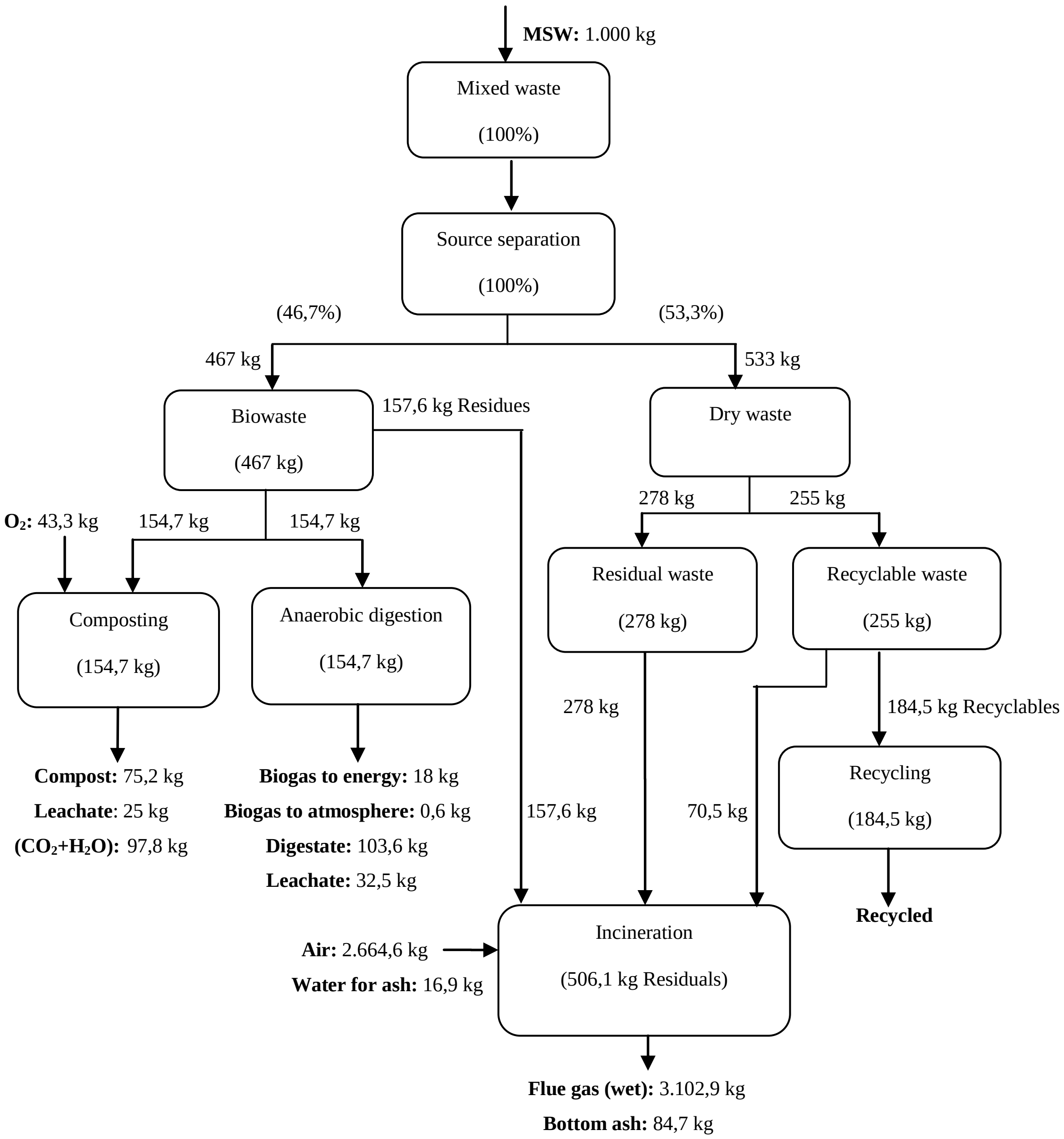

Figure 45. Basic Scenario-4(b) Mass Balance

In B.S-5(a), 367,5 kg of biowaste is sent to the composting process, 178,8 kg of compost, 59,4 kg of leachate, and 232,2 kg of CO_2 and $H_2O_{(gas)}$ are formed as the result of this process. 100 kg of the residual waste is sent to the landfill area, while 321 kg of the residual waste is sent to the incineration process. Landfilling 100 kg of residual waste produces 5,4 kg of CH_4, 14,9 kg of CO_2, and 155,5 kg of leachate. On the other hand, 10,7 kg of water for ash and 1.683,5 kg of air are required for the incineration of 321 kg of residual waste, resulting in 53,7 kg of bottom ash and 1.961,5 kg (1569 m^3) of wet flue gas (Fig 46).

The wet flue gas consists of 274,3 kg of CO_2, 240,7 kg of H_2O, 0,8 kg of SO_2, 5,74 kg of NO_X, 810 kg of N, and 630 kg of the supplied air (l).

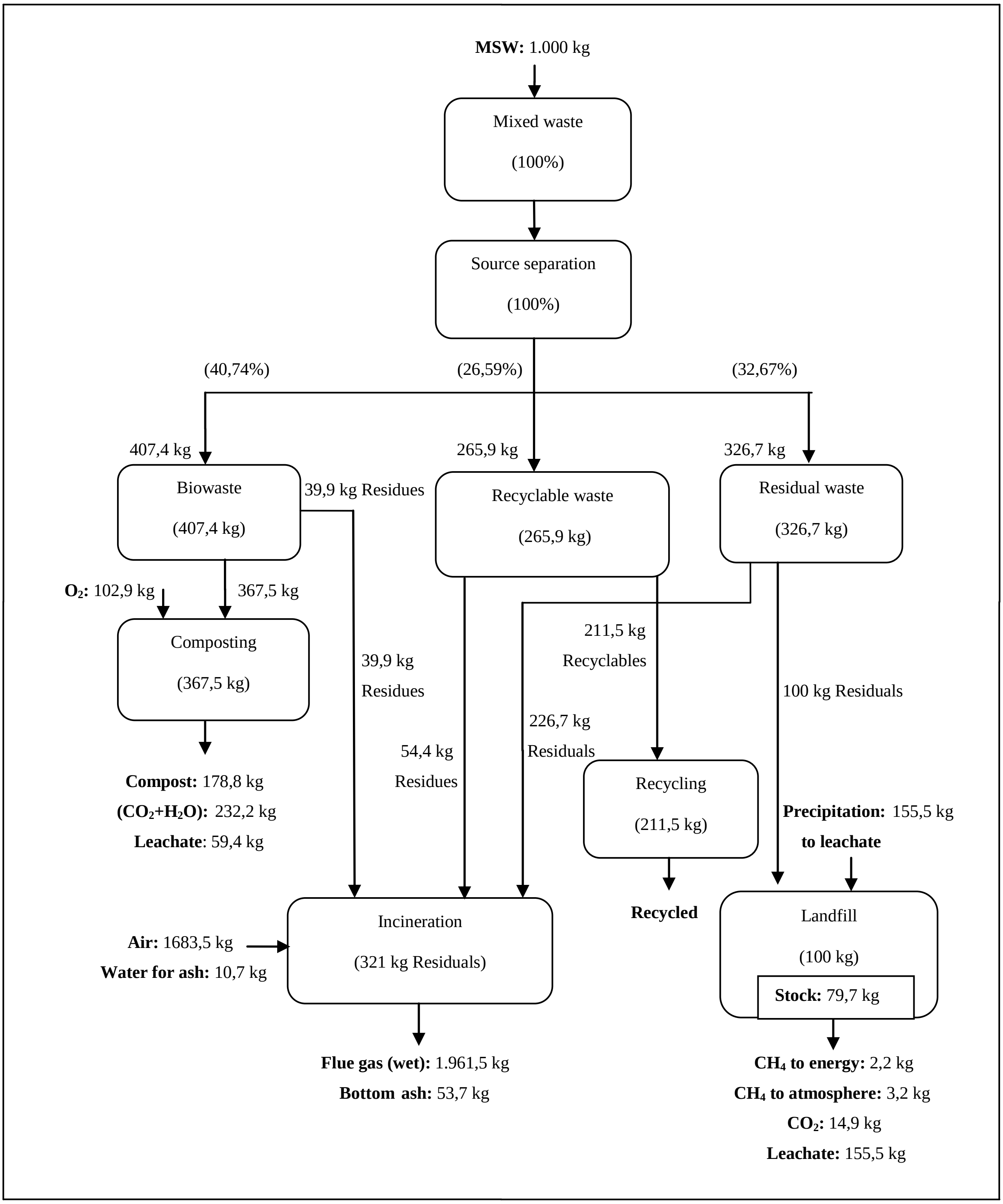

Figure 46. Basic Scenario-5(a) Mass Balance

The disposal process and mass balance results of B.S-5(b) are almost the same as B.S-5(a), the only difference is that the anaerobic digestion process is used instead of the composting process. As a result of anaerobic digestion of 367,5 kg of residual waste, 44,1 kg of biogas, 246,2 kg of digestate, and 77,2 kg of leachate are formed (Fig. 47).

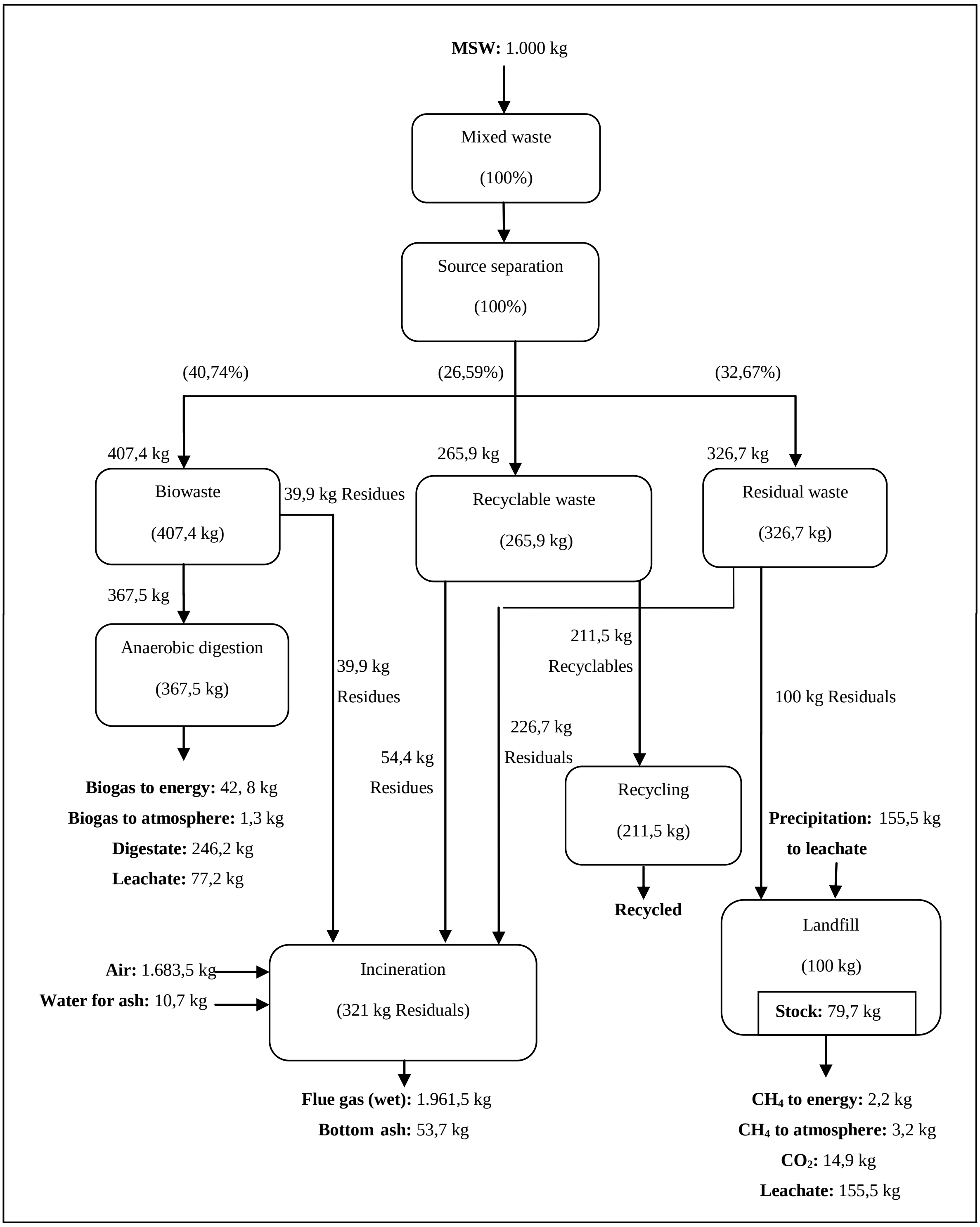

Figure 47. Basic Scenario-5(b) Mass Balance

C.S-1 is the current situation of Istanbul, in which 60 kg of recyclable waste is recycled, 110 kg of the biowaste is sent to the composting process, and the remaining 830 kg of residual waste is sent to the landfill area for disposal. From the disposal of 830 kg of the residual waste by the landfill process without any pre-treatment method, 44,9 kg of CH_4, 123,8 kg of CO_2, and 1.290,6 kg of leachate are generated. Meanwhile, 53,5 kg of compost (28,4 kg fine compost and 25,1 kg coarse compost), 17,8 kg of leachate, 69,5 kg of CO_2, and $H_2O_{(gas)}$ are formed as a result of the composting process (Fig 48).

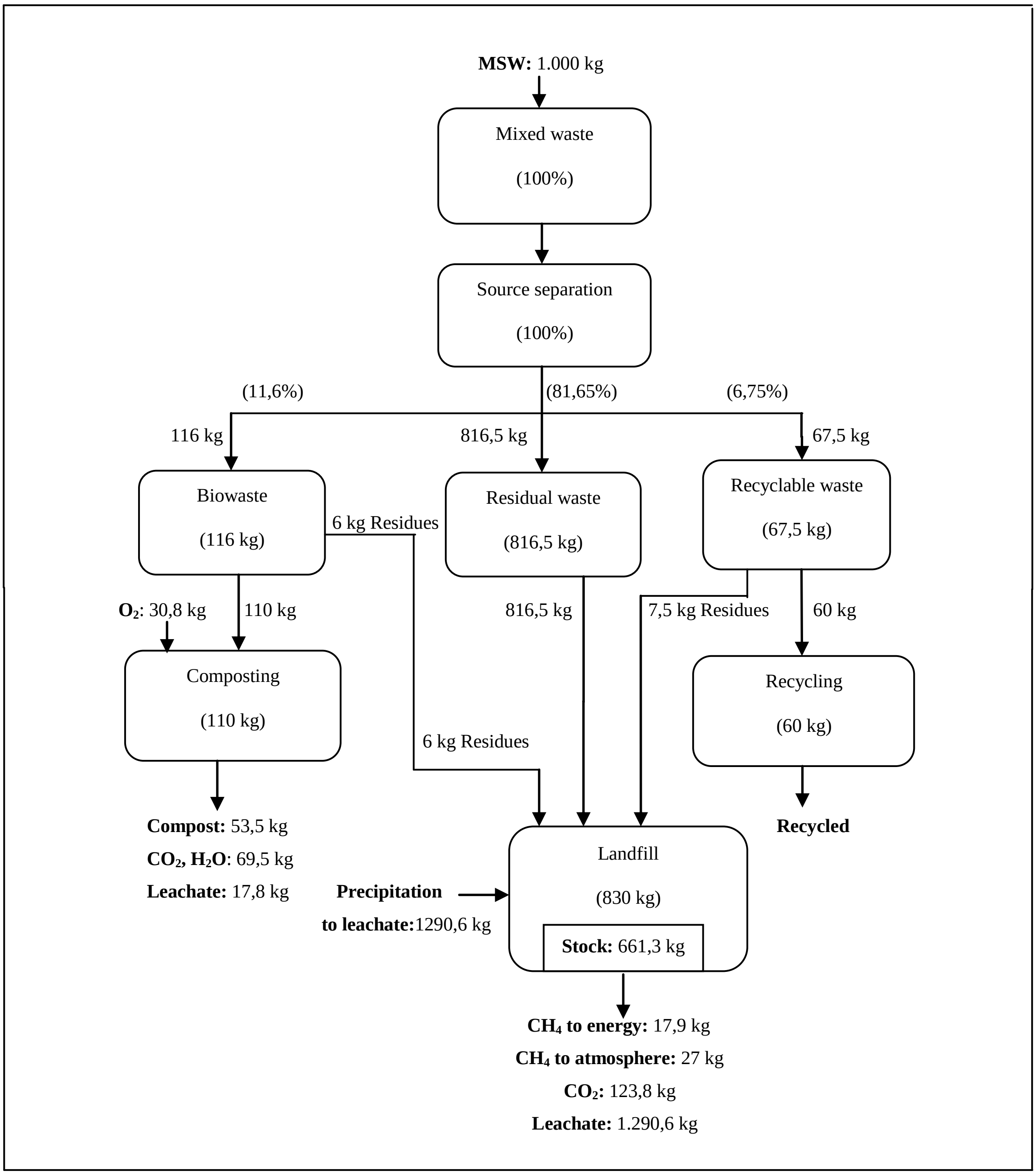

Figure 48. Combination Scenario-1 Mass Balance

C.S-2 comprises recycling, anaerobic digestion, landfill, and incineration process. It is assumed that all 150 kg of recyclable waste is recycled, 250 kg of biowaste is sent to anaerobic digestion, and 350 kg of residual waste is disposed of in the landfill, while 250 kg of residual waste is incinerated. The landfill process generates 19 kg of CH_4, 52,2 kg of CO_2, and 544,2 kg of leachate as output. 30 kg of biogas, 167,5 kg of digestate, and 52,5 kg of leachate are generated as the output in the anaerobic digestion process, while 41,9 kg of bottom ash and 1.528 kg (1.222 m^3) of wet flue gas are generated in the incineration from 250 kg of residual waste (Fig. 49).

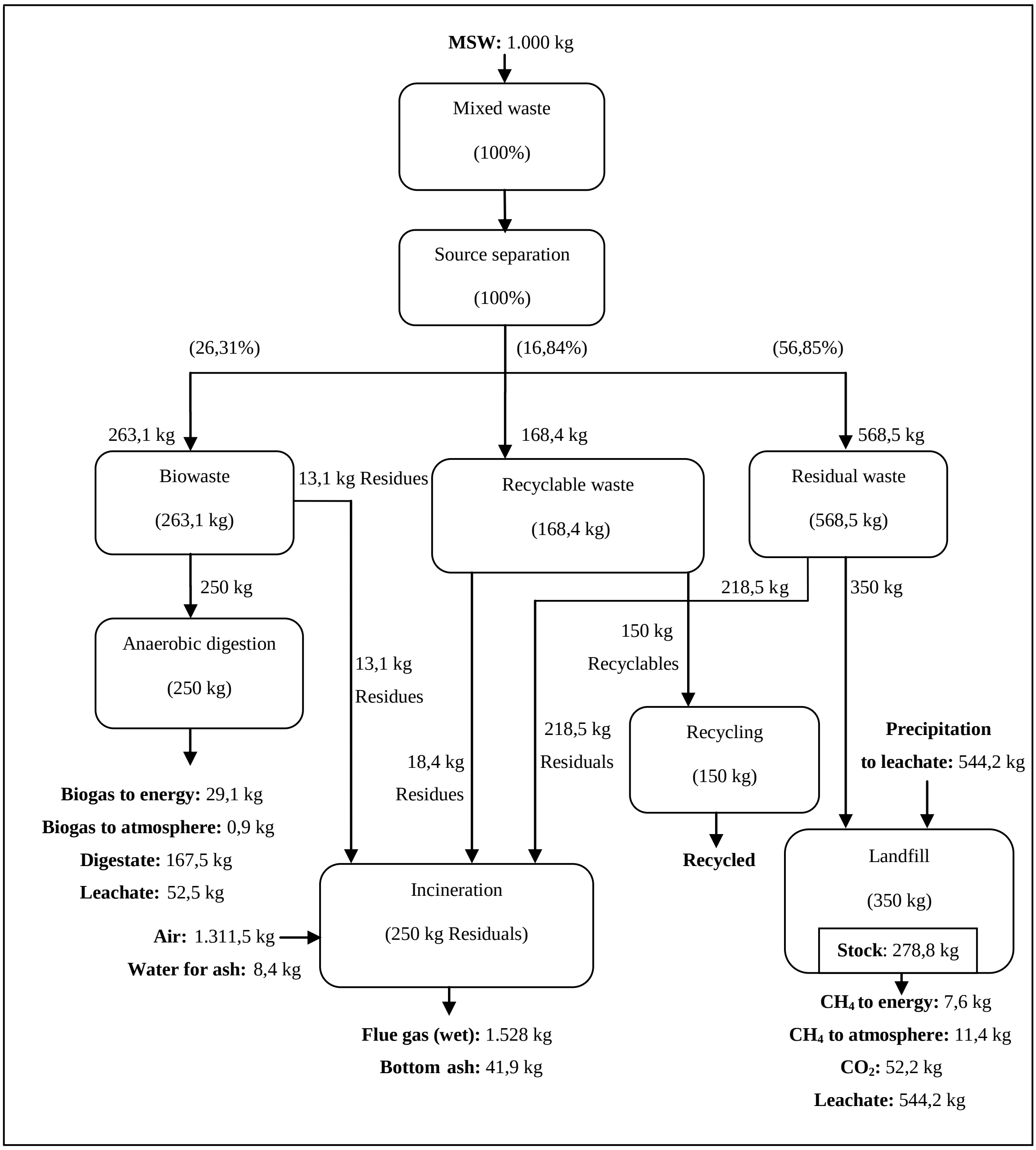

Figure 49. Combination Scenario-2 Mass Balance

C.S-3 comprises recycling, composting, landfill, and incineration process. It is assumed that all 75,3 kg of waste is recycled, 132,3 kg of biowaste is composted, and 542,4 kg of residual waste is disposed of in the landfill, while 250 kg of the residual waste is incinerated. In the landfill process, 29,3 kg of CH_4, 843,4 kg of leachate, and 81 kg of CO_2 are formed, while the composting process results in 64,4 kg of compost (28,4 kg fine compost and 25,1 kg coarse compost), 21,3 kg of leachate, and 83,6 kg of CO_2 and $H_2O_{(gas)}$ (Fig. 50). Mass balance values of the incineration process are the same as the values of C.S-2.

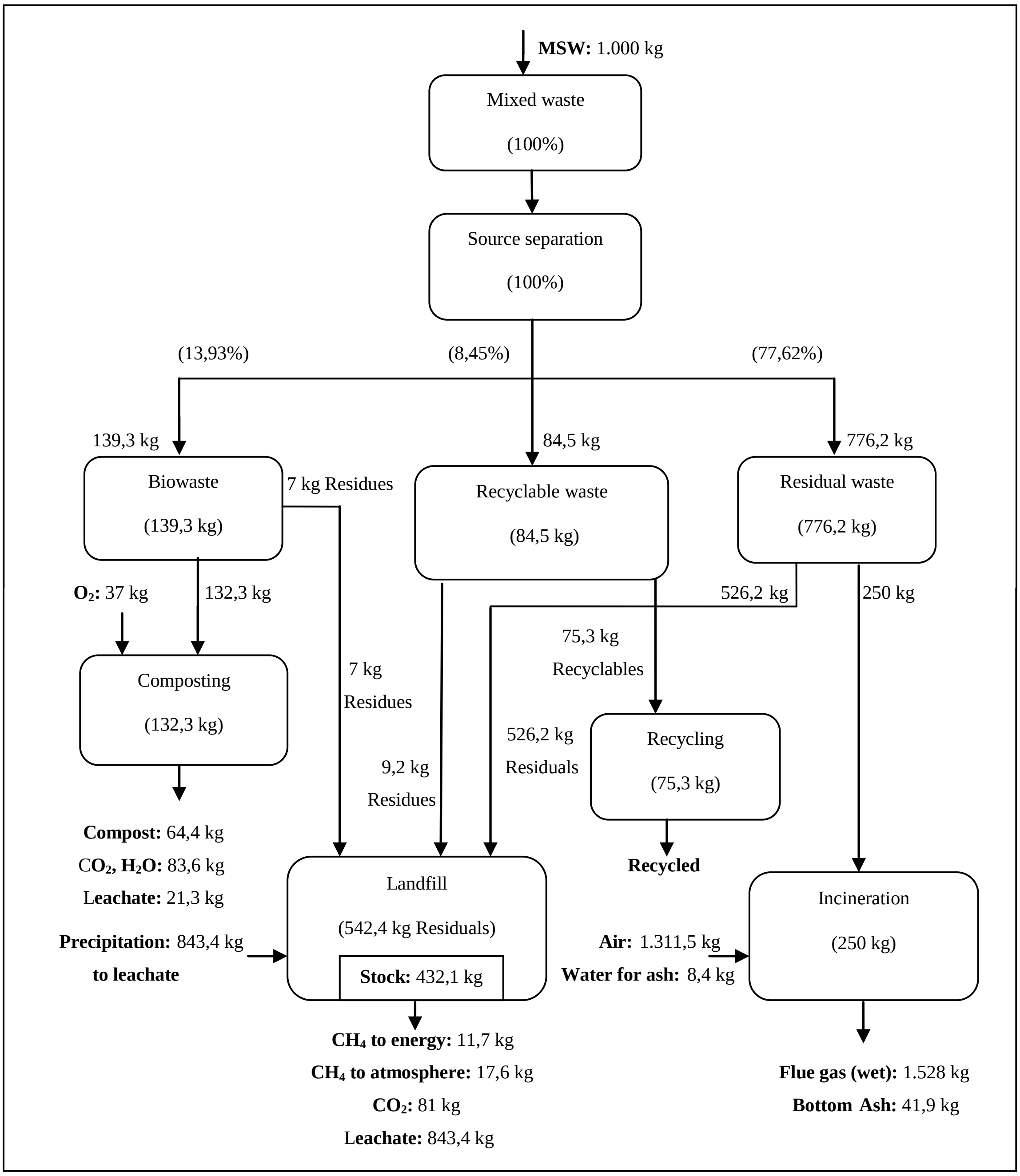

Figure 50. Combination Scenario-3 Mass Balance

6.1.2. Energy Balance Calculation Results

Energy recovery from waste is the conversion of non-recyclable waste materials into useable heat, electricity, or fuel through a variety of processes, including combustion, gasification, pyrolization, anaerobic digestion, and LFG recovery. This process is often called waste-to-energy (WTE). Energy recovery from waste is part of the non-hazardous waste management hierarchy. Converting non-recyclable waste materials into electricity and heat generates a renewable energy source and reduces carbon emissions by offsetting the need for energy from fossil sources and reduces methane generation from landfills (USEPA, 2020).

In the basic and combination scenarios energy balance calculations, energy production from anaerobic digestion, incineration, and landfill are considered. The anaerobic digestion and incineration process residues that are brought to the landfill area, and the amount of anaerobic digestion residue brought to the incineration process, are ignored in the energy balance calculations.

In B.S-1, 0,43 kg of diesel oil with an energy potential of 5,1 kWh and 24,5 kWh of electricity are consumed for the production of 116,7 kWh of electrical energy from 21,6 kg of CH_4 (Fig. 51).

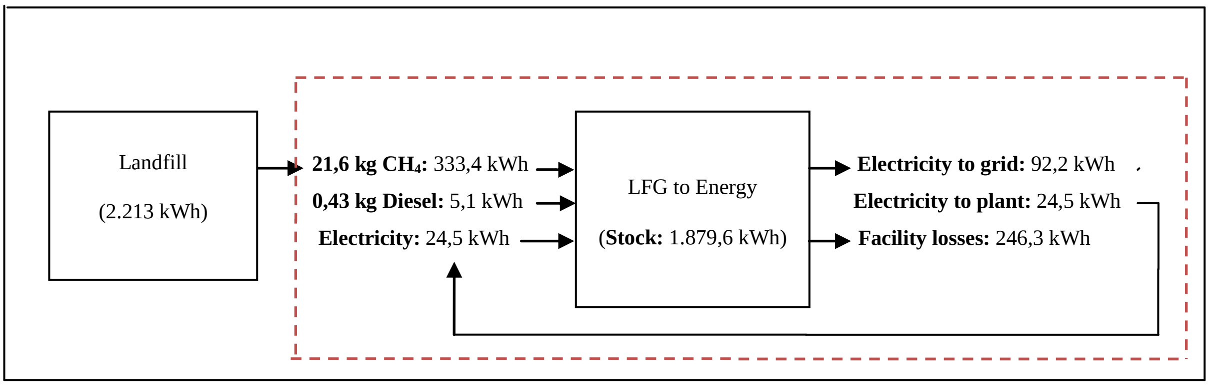

Figure 51. Basic Scenario-1 Energy Balance (Based on 1 Mg MSW)

2.102 kWh of steam is generated, 736 kWh of the steam is converted to electrical energy, while 1.366 kWh of the steam is released as heat energy by incineration of 1 Mg of MSW in B.S-2 (Fig. 52) and B.S-3 (Fig. 53).

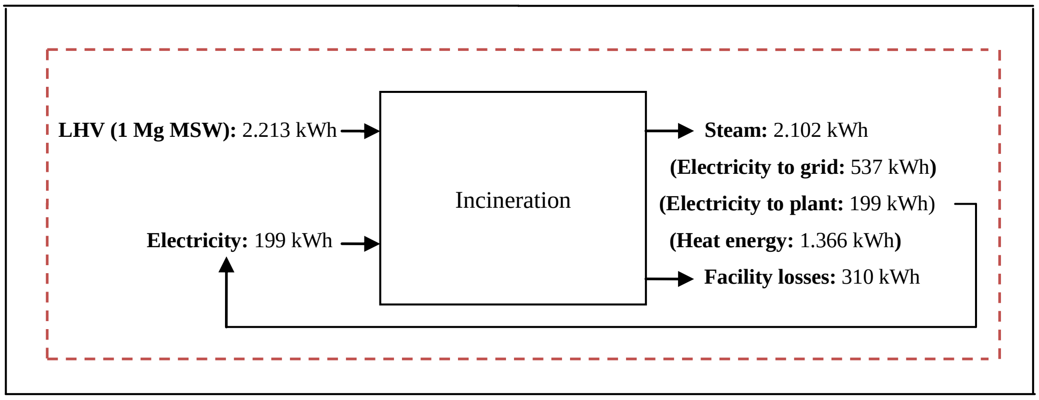

Figure 52. Basic Scenario-2 Energy Balance (Based on 1 Mg MSW)

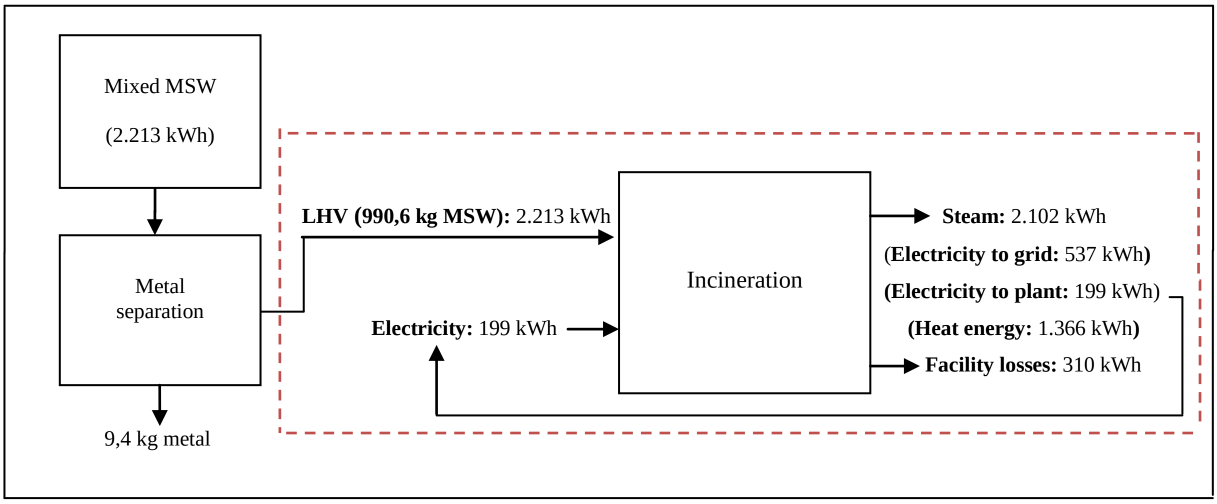

Figure 53. Basic Scenario-3 Energy Balance (Based on 1 Mg MSW)

The energy is produced from the biogas incineration and the LFG incineration process in B.S-4(a). 86,4 kWh of total energy (33,6 kWh as electricity and 52,8 kWh as heat) is produced from the incineration of 15 m^3 of biogas, while only 59 kWh of electrical energy is produced from 10,9 kg of CH_4 in the landfill process (Fig.54).

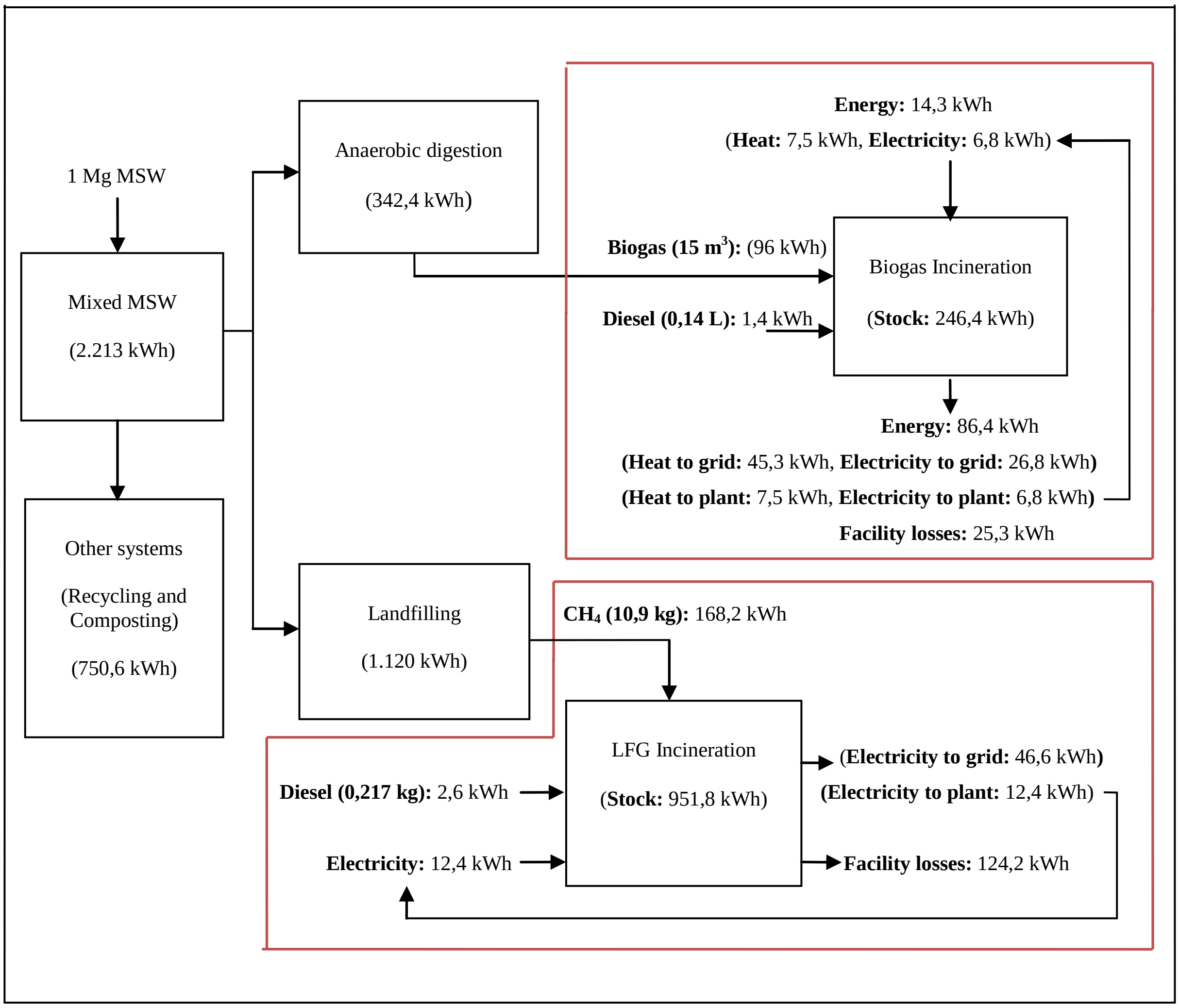

Figure 54. Basic Scenario-4(a) Energy Balance (Based on 1 Mg MSW)

B.S-4(b) energy production values of the anaerobic digestion are the same as the values of B.S-4(a). 86,4 kWh of total energy is obtained (33,6 kWh as electricity and 52,8 kWh as heat) from the incineration of 15 m^3 of biogas, while 1.064 kWh of steam is produced. Additionally, 372,4 kWh of the steam energy is converted to electrical energy, and 691,6 kWh of energy is released as heat energy by incineration of 506,1 kg residual waste in B.S-4(b) (Fig. 55).

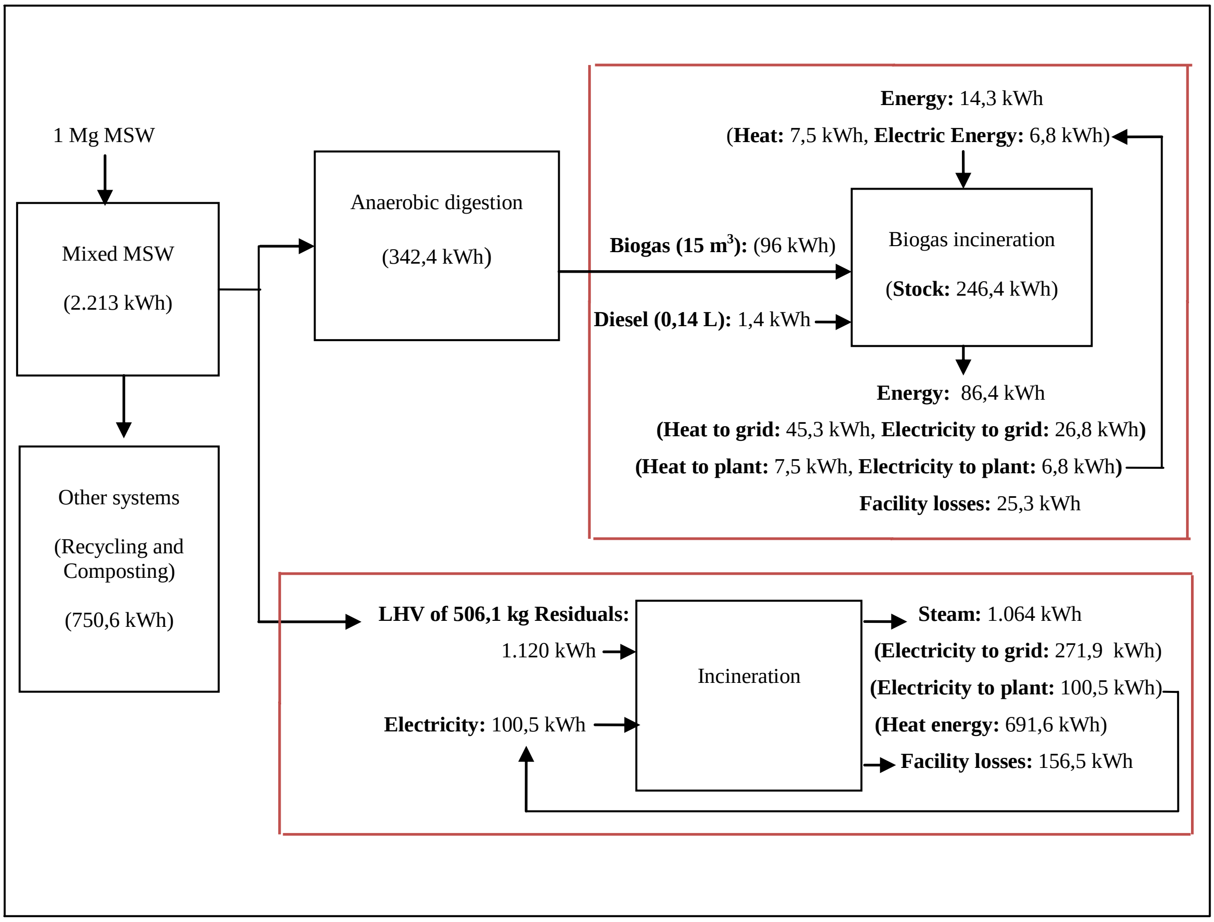

Figure 55. Basic Scenario-4(b) Energy Balance (Based on 1 Mg MSW)

Energy production is provided from the landfill and incineration process in B.S-5(a) (Fig. 56), while energy production is provided from the anaerobic digestion process, as well as landfill and incineration, in B.S-5(b) (Fig. 57). 11,8 kWh of electrical energy is generated from 2,2 kg of CH_4 as a result incineration of LFG, 236,2 kWh of electrical energy and 438,7 kWh of heat energy are produced by incineration of 321 kg of residual waste in B.S-5(a) and B.S-5(b). In addition, 205,4 kWh of energy (79,9 kWh electricity and 125,5 kWh heat) is generated from the incineration of 35,65 m^3 of biogas in B.S-5(b).

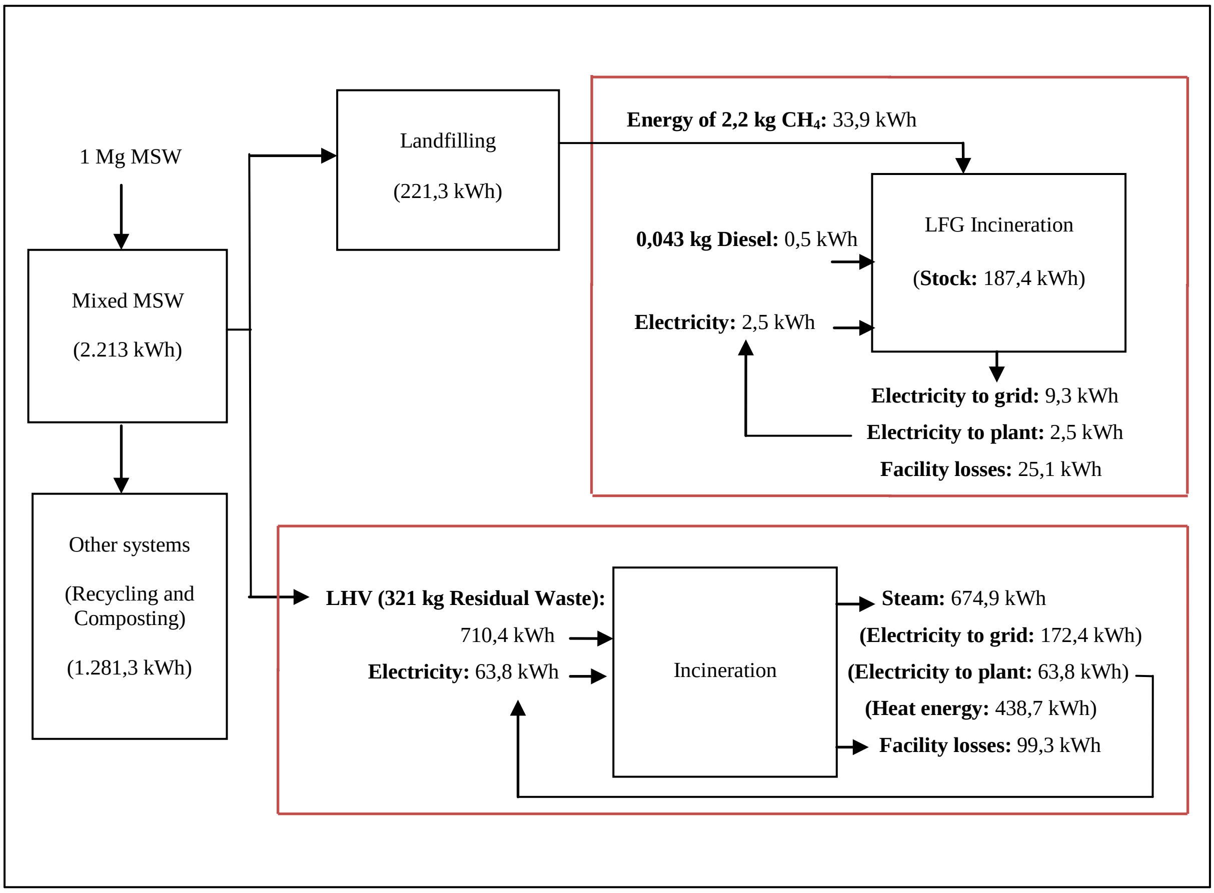

Figure 56. Basic Scenario-5(a) Energy Balance (Based on 1 Mg MSW)

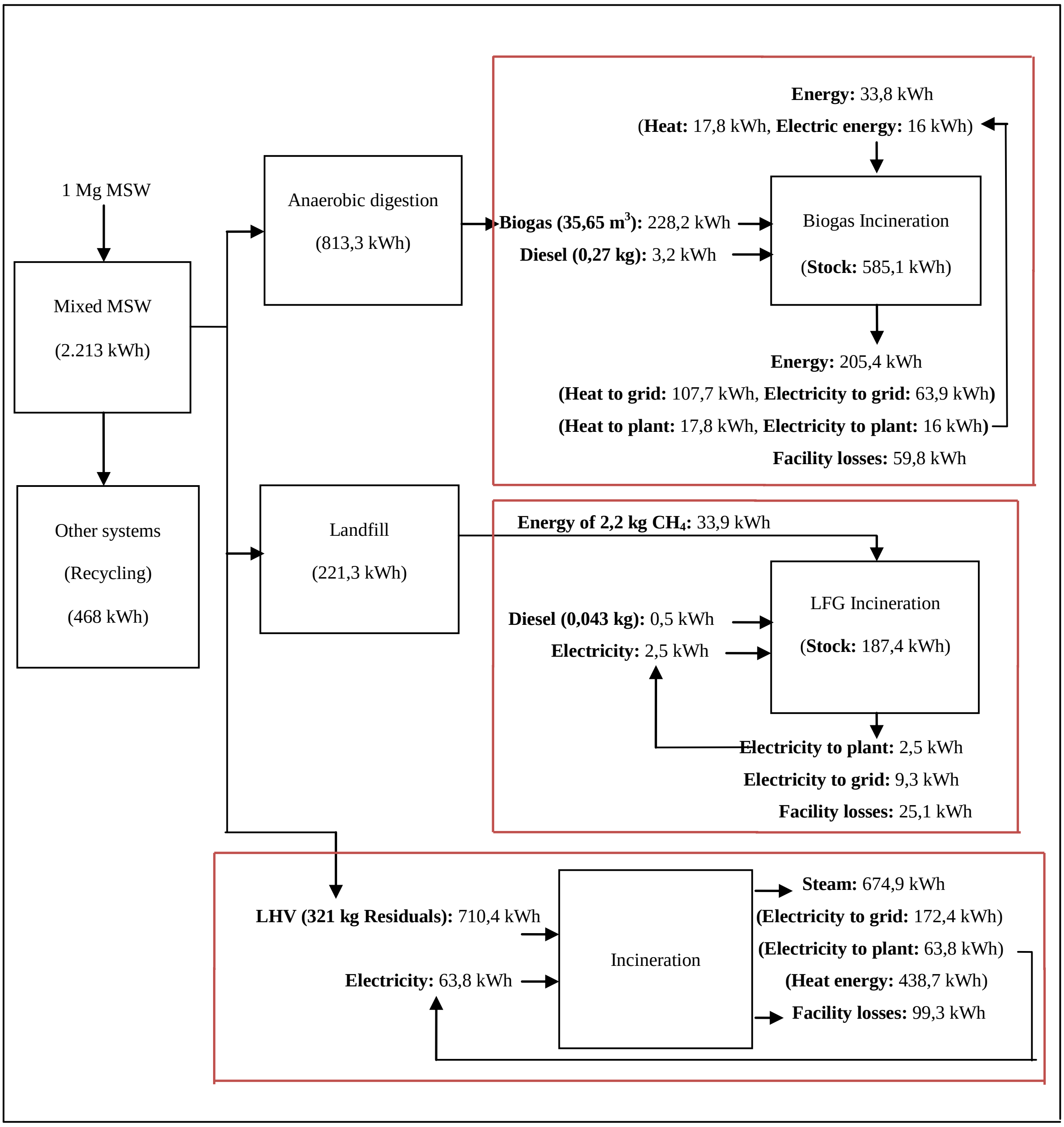

Figure 57. Basic Scenario-5(b) Energy Balance (Based on 1 Mg MSW)

Energy production in C.S-1 is realized from only the landfill process. 96,7 kWh of electrical energy is obtained from 17,9 kg of CH_4 in LFG, while 20,3 kWh of electrical energy and 0,36 kg of diesel oil, which corresponds to 4,3 kWh of energy, are consumed in this process (Fig.58).

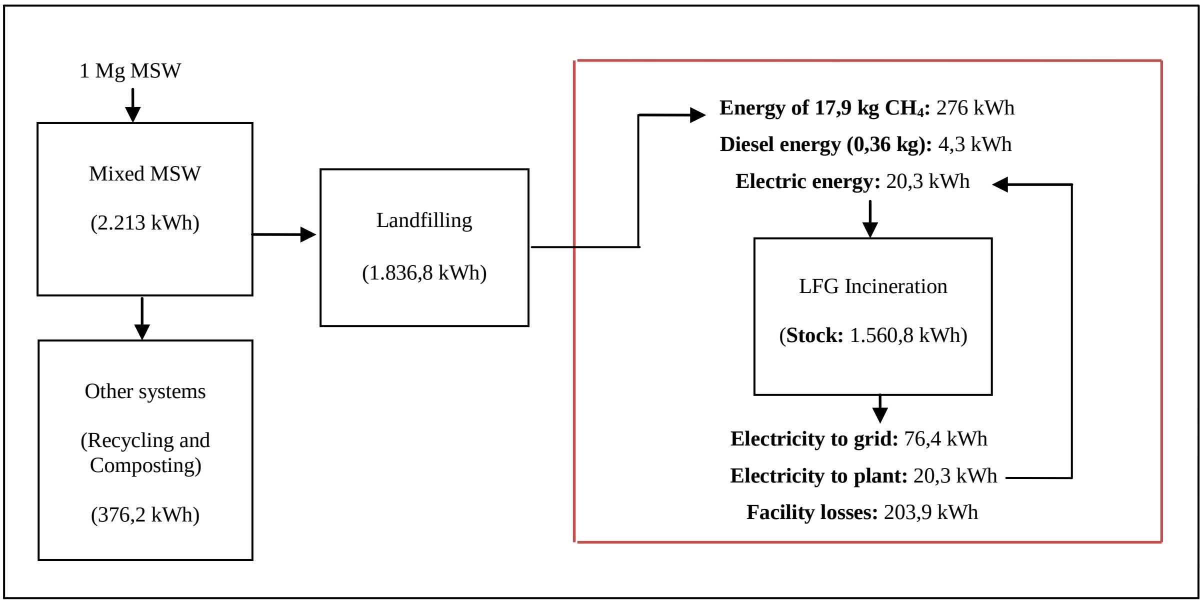

Figure 58. Combination Scenario-1 Energy Balance (Based on 1 Mg MSW)

In C.S-2, 139,7 kWh of total energy (54,3 kWh of electricity and 85,4 kWh of heat) is generated from the incineration of 24,25 m^3 of biogas. Additionally, 41 kWh of electrical energy is generated from 7,6 kg of CH_4 in the landfill process, and 525,5 kWh of steam is generated by incineration of 250 kg of residual waste. Furthermore, 184 kWh of the steam is converted to electrical energy, while 341,5 kWh of the steam is released as heat energy (Fig.59).

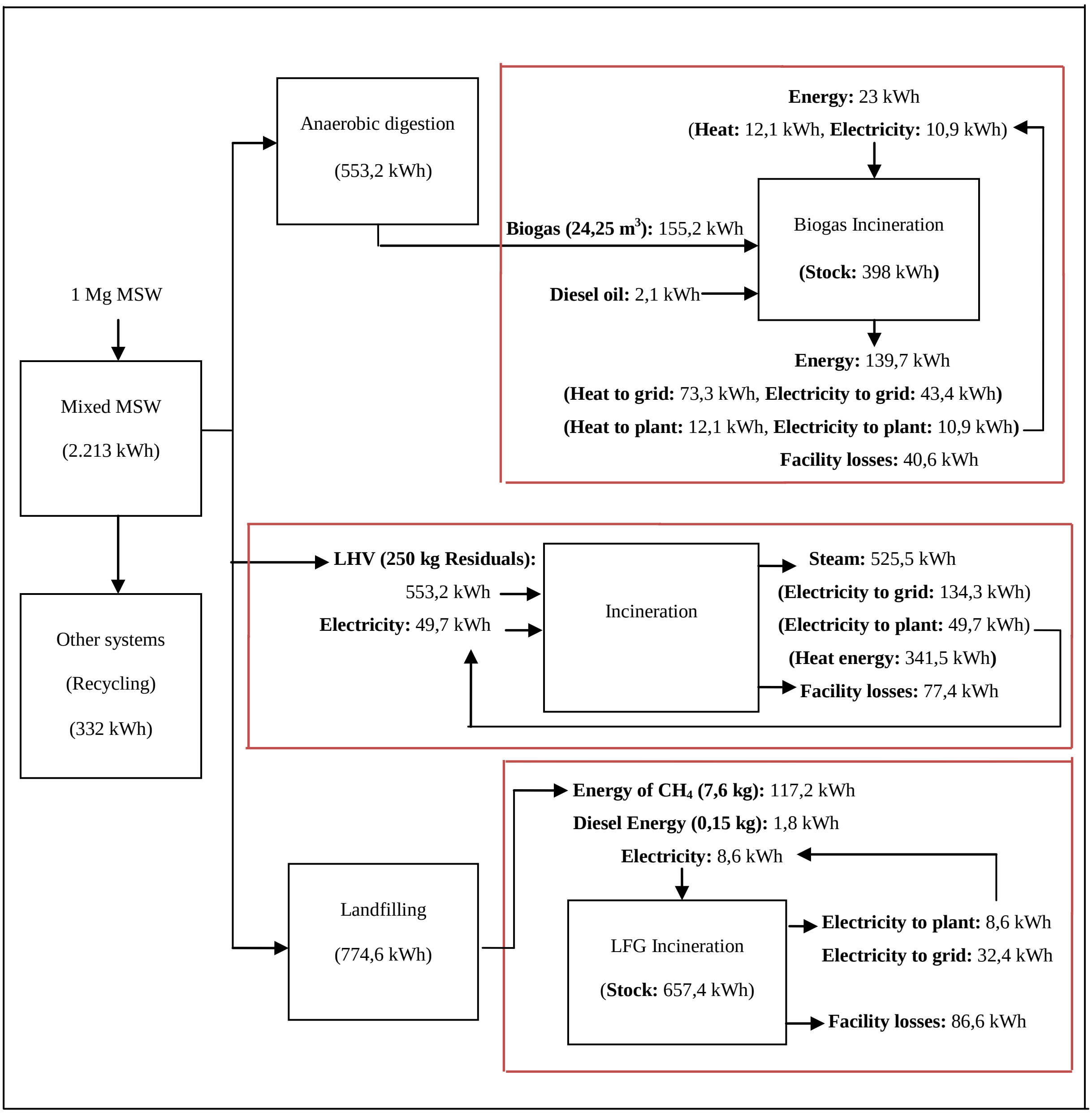

Figure 59. Combination Scenario-2 Energy Balance (Based on 1 Mg MSW)

Energy production is 63,2 kWh of electrical energy from 11,7 kg of CH_4 in the landfill process, while 184 kWh of electrical energy and 341,5 kWh of heat energy are produced by the incineration of 250 kg of residual waste in C.S-3 (Fig.60).

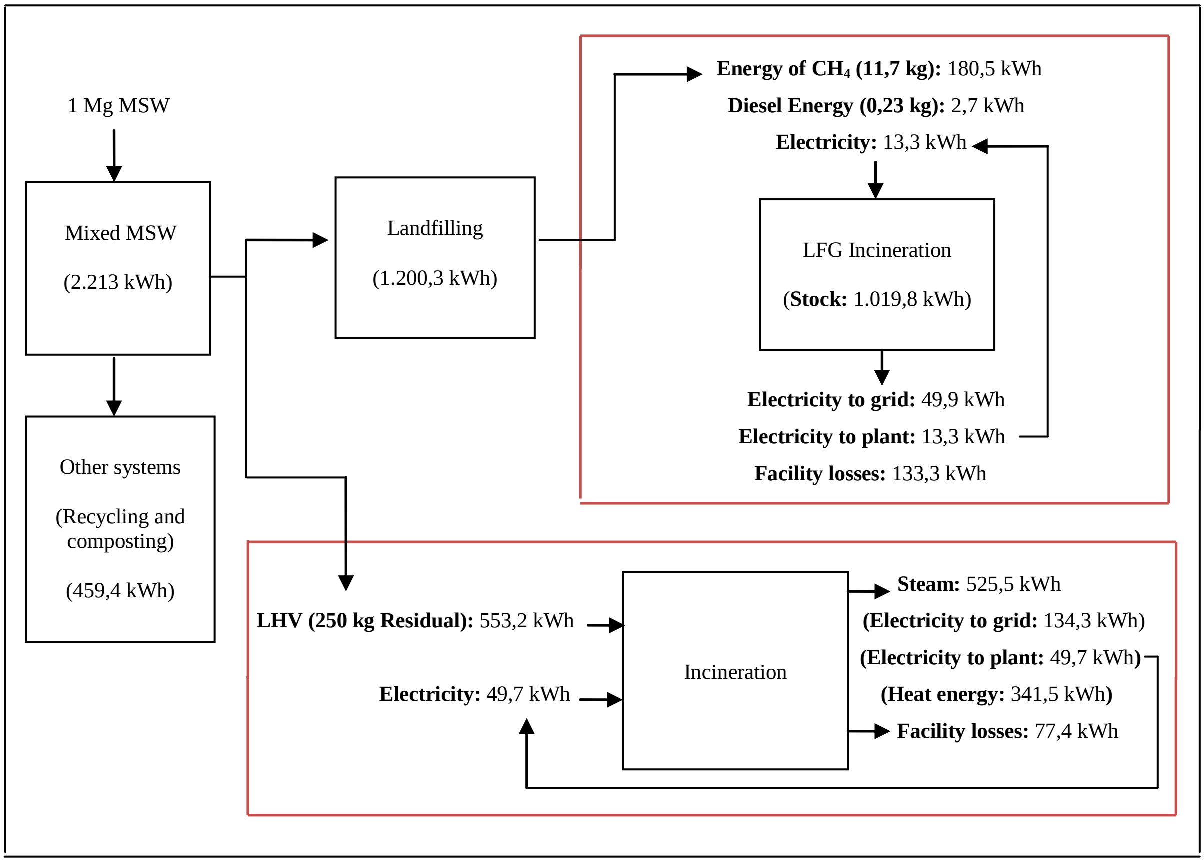

Figure 60. Combination Scenario-3 Energy Balance (Based on 1 Mg MSW)

6.2. Comparison of GHG and Energy Balance Results of Basic and Combination Scenarios

GHG balance calculations of the basic and combination scenarios are made according to the net GHG values of disposal options obtained in Chapter 5.3. GHG emission balance inventory analysis section. The calculations in the inventory analysis are made according to the treatment of 1 Mg of MSW as the functional unit (Table 36).

Based on the GHG and avoided product inventory analysis (Chapter 5.3), net GHG generation because of energy production in landfill, composting, anaerobic digestion, and incineration are calculated as 908,6 kg CO_2 eq, 69,9 kg CO_2 eq, 34,6 kg CO_2 eq, and 308,3 kg CO_2 eq respectively. However, 92,2 kWh of energy is saved in the energy production stage from LFG in the landfill process, 48,84 kWh of energy, and 13,6 kg CO_2 eq GHG are saved using 258,4 kg of compost as a fertilizer from the composting process, 99,25 kWh of energy is saved using 525 kg compost (obtained from 670 kg of digestate) as a fertilizer, and 27,6 kg CO_2 eq GHG are saved on both energy production from biogas and compost used as fertilizer. Additionally, 308,3 kg CO_2 eq GHG and 1.903 kWh of energy are saved on the energy production in the incineration process. Apart from these, 187 kg CO_2 eq GHG and 1.404,7 kWh (5.502,82 MJ) of energy are saved as a result of recycling 297,7 kg of recyclable waste (amount of recyclables in 1 Mg MSW based on MSW characterization data of ISTAC, 2018).

Table 36. GHG Generation and Energy Balances of Waste Treatment Processes (based on 1 Mg of MSW)

	GHG Generation	Avoided GHG Emission	Net GHG Generation	Net Energy Production	Avoided Energy	Net Avoided Energy
	(kg CO_2 eq)			(kWh)		
Composting	69,9	13,6	56,3	-	48,84	48,84
Anaerobic Digestion	34,6	27,6	7	466,6	99,25	565,85
Landfill	908,6	-	908,6	92,2	-	92,2
Incineration	308,3	-	308,3	1.903	-	1.903

6.2.1. GHG Calculations of Basic and Combination Scenarios

GHG emission and energy values of basic and combination scenarios are calculated based on the values in Table 36.

- **Basic Scenario-1**

B.S-1 includes only the landfill process, and the amount of GHG generation in this scenario comprises the non-combustible part of CH_4 within LFG that is released into the atmosphere and diesel consumption in the energy production phase from LFG. Accordingly, the amount of GHG generation in B.S-1 is found as 908,6 kg CO_2 eq with the multiplication of 32,4 kg of CH_4 released into the atmosphere by 28 kg CO_2 eq GWP of CH_4.

- **Basic Scenario-2**

B.S-2 includes only the incineration process, and the amount of GHG generation is equal to 308 kg CO_2 eq, which is the amount of CO_2 fossil caused by 736 kWh of electricity production from 1 Mg of MSW in this scenario.

- **Basic Scenario-3**

GHG generation is caused by incineration of 990,6 kg MSW, and this value is the same as the GHG value of B.S-2, at 308 kg CO_2 eq. In addition, 43,1 kg CO_2 eq GHG saving is realized with the recycling of 9,4 kg metal. Based on these values, the net GHG generation decreases to 264,9 kg CO_2 eq with the recycling of 9,4 kg metal.

- **Basic Scenario-4(a)**

Total GHG emission in B.S-4(a) is equal to 476,8 kg CO_2 eq, which is the sum of GHG values released from landfill, composting, and anaerobic digestion processes. The total avoided GHG is 122,1 kg CO_2 eq in this scenario, which originates from recycling, composting, and anaerobic digestion process.

- **Basic Scenario-4(b)**

Total GHG emission emerges from composting, landfill, and incineration processes in B.S-4(b), and total GHG is calculated as 172,6 kg CO_2 eq, while the total avoided GHG is 122,1 kg CO_2 eq in this scenario.

- **Basic Scenario-5(a)**

Total GHG emission is calculated as 214,2 kg CO_2 eq in B.S-5(a). This amount of GHG generation is the sum of GHG values originating from composting, landfill, and incineration processes. The total avoided GHG is calculated as 137,8 kg CO_2 eq in this scenario.

- **Basic Scenario-5(b)**

GHG emission is calculated as 201,1 kg CO_2 eq, while the total avoided GHG is calculated as 143 kg CO_2 eq in B.S-5(b). The GHG generation emerges from anaerobic digestion, landfill, and incineration processes, while avoiding GHG generation is realized in recycling and anaerobic digestion processes.

- **Combination Scenario-1**

GHG emission is calculated as 765 kg CO_2 eq, originating from composting and landfill processes in C.S-1, which is the current MSWM scenario of Istanbul. The total avoided GHG is 39,2 kg CO_2 eq originating from the recycling and composting process in this scenario.

• **Combination Scenario-2**

GHG emission is calculated as 405,3 kg CO_2 eq, originating from composting and landfill processes in C.S-2, and the total avoided GHG is found as 101,1 kg CO_2 eq.

• **Combination Scenario-3**

Totally, 579,7 kg CO_2 eq GHG emission emerge from composting and landfill processes and the avoided GHG from the recycling and composting process is calculated as 49,1 kg CO_2 eq in C.S-3.

• **Comparison of the Scenarios**

GHG generation and avoided GHG values of the waste disposal process mentioned above are shown in Table 36. In addition, net GHG values of the scenarios are shown in Table 37. These values are calculated by subtracting the avoided GHG values from the GHG generation values:

• **Net GHG** = GHG Generation – Avoided GHG

Table 37. GHG Calculations of Basic and Combination Scenarios (based on 1 Mg MSW)

	GHG Generation (kg CO_2 eq)					Avoided GHG (kg CO_2 eq)				Net GHG
	Landfill	**Incineration**	**Compost.**	**A.D.**	**Total**	**Recycling**	**Compost.**	**A.D.**	**Total**	
B.S-1	908,6	-	-	-	908,6	-	-	-	-	908,6
B.S-2	-	308	-	-	308	-	-	-	-	308
B.S-3	-	308	-	-	308	43,1	-	-	43,1	264,9
B.S-4(a)	460	-	10,8	5,97	476,8	115,7	2,1	4,3	122,1	354,7
B.S-4(b)	-	155,8	10,8	5,97	172,6	115,7	2,1	4,3	122,1	50,5
B.S-5(a)	89,7	98,8	25,7	-	214,2	132,8	5	-	137,8	76,4
B.S-5(b)	89,7	98,8	-	12,6	201,1	132,8	-	10,15	143	58,1
C.S-1	757,2	-	7,7	-	765	37,68	1,5	-	39,2	725,8
C.S-2	319,7	77	-	8,64	405,3	94,2	-	6,9	101,1	304,2
C.S-3	493,5	77	9,25	-	579,7	47,3	1,8	-	49,1	530,6

6.2.2. Energy Calculations of Basic and Combination Scenarios

- **Basic Scenario-1**

B.S-1 includes only the landfill process, and the energy production is calculated as 116,7 kWh of electrical energy, which is generated by the incineration of 21,6 kg of CH_4 in the LFG energy plant. The avoided energy is calculated as 92,2 kWh because 24,5 kWh of the produced energy is consumed in the plant.

- **Basic Scenario-2**

B.S-2 includes only the incineration process, and the net energy is calculated as 1.903 kWh of heat and electrical energy, which is obtained from the incineration of 1Mg MSW. This value is also equal to the net avoided energy.

- **Basic Scenario-3**

B.S-3 comprises of 9,4 kg metal recycling in addition to the incineration process. The energy sent to the grid is 1.903 kWh, which is obtained from incineration of 990,6 kg MSW. In addition, 137 kWh of energy saving is realized with the recycling of 9,4 kg of metal. Based on these values, the net energy is calculated as 2.040 kWh in this scenario.

- **Basic Scenario-4(a)**

The energy sent to the grid is calculated as 118,8 kWh, originating from landfill and anaerobic digestion processes, and the avoided energy is calculated as 893,5 kWh based on recycling, composting, and anaerobic digestion process in B.S-4(a). Based on these values, the net energy of this scenario is calculated as 1.012,3 kWh.

- **Basic Scenario-4(b)**

The avoided energy value of B.S-4(b) is 893,5 kWh, which is the same as the avoided energy value of B.S-4(a), while total net energy is calculated as 1.035,6 kWh. Based on these values, the total net avoided energy is found to be 1.929,1 kWh.

- **Basic Scenario-5(a)**

The energy production sent to the grid is calculated as 620,4 kWh from landfill and incineration process in B.S-5(a). Avoided energy originating from composting and recycling processes is determined as 1.016 kWh, and the net energy is found to be 1.636,4 kWh.

- **Basic Scenario-5(b)**

The energy value of B.S-5(b) sent to the grid is determined as 792 kWh, while the avoided energy is calculated as 1.034,4 kWh originating from recycling and anaerobic digestion. The net energy is calculated as 1.826,4 kWh.

- **Combination Scenario-1**

C.S-1 consists of the current MSWM of Istanbul, and the energy is obtained only from the landfill process in this scenario. The calculated net energy is 364,9 kWh, which comprises 76,4 kWh of energy sent to the grid and 288,5 kWh of avoided energy.

- **Combination Scenario-2**

C.S-2 comprises recycling, anaerobic digestion, landfill, and incineration processes, and this scenario reflects the MSWM targets of IMM. The net energy is calculated as 1.357,5 kWh, which comprises 624,9 kWh of energy sent to the grid and 732,6 kWh of avoided energy from the recycling and composting process.

- **Combination Scenario-3**

C.S-3 is developed as a transition scenario that can be implemented in the current situation to improve the current MSWM of Istanbul. This scenario includes composting, recycling, landfill, and incineration processes. The energy production sent to the grid is calculated as 525,7 kWh, and the avoided energy is calculated as 361,8 kWh, originating from recycling and composting processes. The net energy is calculated as 887,5 kWh with the sum of the energy sent to the grid and the avoided energy.

- **Comparison of the Scenarios**

Net energy and avoided energy values of basic and combination scenarios mentioned above are shown in Table 37. In addition, the net avoided energy values of the scenarios are shown in Table 38. These values are calculated by summing the energy sent to the grid and the avoided energy values:

- **Net energy** = Energy to grid + Avoided energy

Table 38. Energy Calculations of Basic and Combination Scenarios (based on 1 Mg MSW)

	Energy to grid (kWh)				Avoided Energy (kWh)				Net Energy
	Landfill	Incineration	A.D.	Total	Recycling	Compost.	A.D.	Total	
B.S-1	92,2	-	-	92,2	-	-	-	-	92,2
B.S-2	-	1.903	-	1.903	-	-	-	-	1.903
B.S-3	-	1.903	-	1.903	137	-	-	137	2.040
B.S-4(a)	46,7	-	72,1	118,8	870,6	7,6	15,3	893,5	1.012,3
B.S-4(b)	-	963,5	72,1	1.035,6	870,6	7,6	15,3	893,5	1.929,1
B.S-5(a)	9,3	611,1	-	620,4	998	18	-	1.016	1.636,4
B.S-5(b)	9,3	611,1	171,6	792	998	-	36,4	1.034,4	1.826,4
C.S-1	76,4	-	-	76,4	283,1	5,37	-	288,5	364,9
C.S-2	32,4	475,8	116,7	624,9	707,8	-	24,8	732,6	1.357,5
C.S-3	49,9	475,8	-	525,7	355,3	6,46	-	361,8	887,5

6.2.3 Results of the Scenarios regarding GHG Emissions and Energy Balances

Based on the calculated GHG emissions and energy values of the basic and combination scenarios in Table 37 and Table 38, the highest net GHG emission of 908,6 kg CO_2 eq is released from B.S-1, where all of the MSW is disposed of in the landfill. The second highest net GHG emission of 757,2 kg CO_2 eq is emitted from C.S-1 (Current MSWM of Istanbul) due to the higher percentage of landfilled waste. Furthermore, B.S-1 has the lowest net energy value of 92,2 kWh, and C.S-1 has the second lowest net energy value with 364,9 kWh.

B.S-3 (9,4 kg metal recycling + 990,6 kg MSW incineration) has the highest net energy value among all scenarios, with 2.040 kWh. B.S-4(b) follows with the second highest net energy value of 1.929,1 kWh, and B.S-3 is close behind with a net energy of 1.903 kWh. Actually, the energy values sent to the grid for B.S-2 and B.S-3 are the same at 1.903 kWh, but B.S-3 achieves 137 kWh of energy savings with 9,4 kg metal recycling, increasing the net energy value to 2.040 kWh.

B.S-4(b) produces 50,5 kg CO_2 eq, which is the lowest net GHG value among all scenarios because this scenario does not include the landfill process for MSW. In this scenario 309,4 kg of biowaste (60% of the total biowaste) is disposed of through composting and anaerobic digestion, 184,5 kg of recyclable dry waste (62% of the total recyclable dry waste) is recycled, and 506,1 kg of residual waste is incinerated. B.S-4(b) also has the highest net energy value of 1.929,1 kWh due to the higher percentage of incinerated waste following B.S-3.

B.S-5(b) and B.S-5(a), developed according to EU waste legislation targets, have the lowest net GHG emissions after B.S-4(b). The second lowest net GHG emission is 58,1 kg CO_2 eq emitted from B.S-5(b), with B.S-5(a) following with 76,4 kg CO_2 eq net GHG emission. Furthermore, B.S-5(b) and B.S-5(a) have relatively higher net energy values.

C.S-3, a transition scenario applicable to Istanbul urgently, has the third highest net GHG emission due to the relatively higher percentage of landfilled waste. On the other hand, C.S-2, developed based on the IMM MSWM target of Istanbul, has much lower net GHG value and higher net energy value compared to the values of C.S-1 and C.S-3.

All calculated GHG production, net GHG, energy production, and net avoided energy values of basic and combination scenarios are illustrated in Fig. 61.

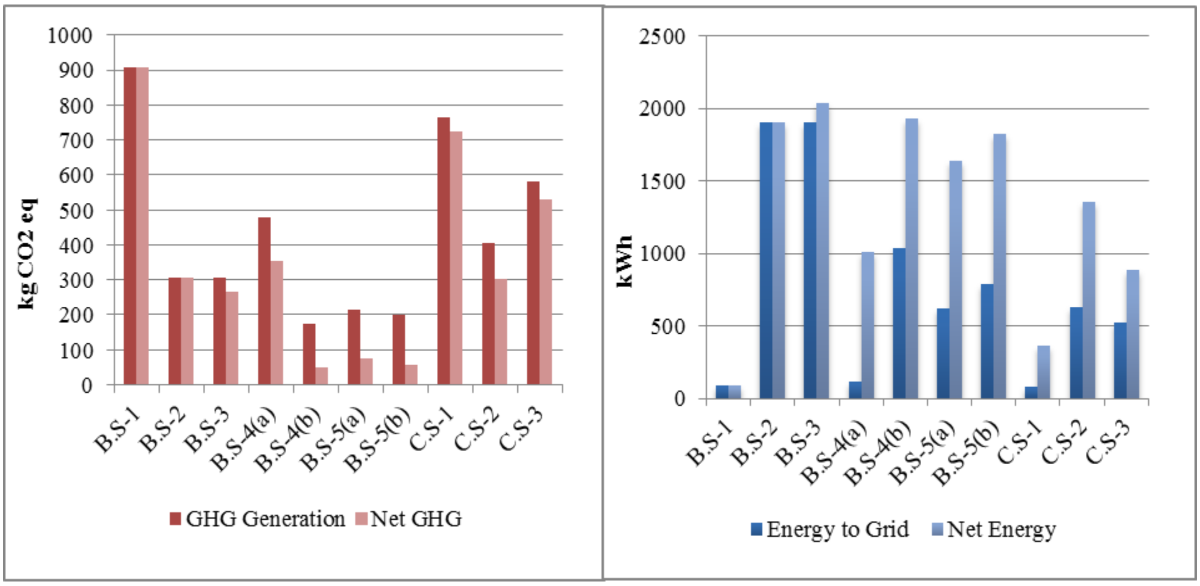

Figure 61. GHG Emissions and Energy Values of Basic and Combination Scenarios

6.2.4. Avoided GHG Emissions of Basic and Combination Scenarios in the Aspect of Energy Substitution based on Türkiye Energy Production

According to MENR (2020), Türkiye produced 306,703 TWh of electrical energy by the year 2020. Of the total energy production, 34,5% (105,812 TWh) came from coal, 0,1% (0,323 TWh) from petrol, 23,13% (70,931 TWh) from natural gas, 1,87% (5,737 TWh) from bioenergy and waste, and 40,4% (123,9 TWh) from renewable energy sources (wind, geothermal, hydraulic, and solar) (Fig. 62). Based on these data, 57,73% (177,066 TWh) of electrical energy was generated from fossil sources, which include coal, petrol, and natural gas.

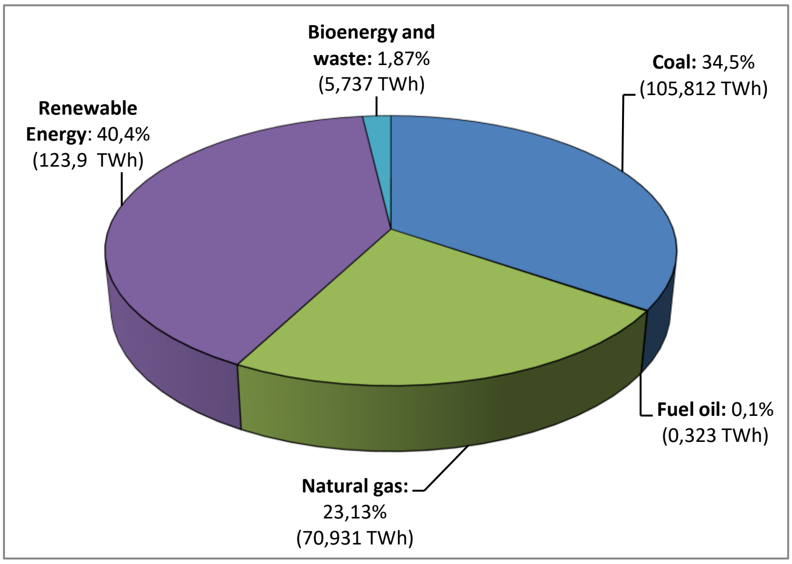

Figure 62. Türkiye Electricity Generation by Source, 2020 (MENR, 2020) (based on 306,703 TWh)

According to MENR (2020), Türkiye produced 34,66 TWh of heat energy from combined heat and power generation by the year 2020. Of the total heat energy production, 25,34% (8,78 TWh) supplied from coal, 4,85% (1,68 TWh) from gaseous fuel, 4,24% (1,47 TWh) from fuel oil, 61,73% (21,4 TWh) from natural gas, and 3,84% (1,33 TWh) from bioenergy and waste (Fig. 63). Based on these values, 93% (33,33 TWh) of the heat energy is sourced from fossil fuels (coal, fuel oil, and natural gas).

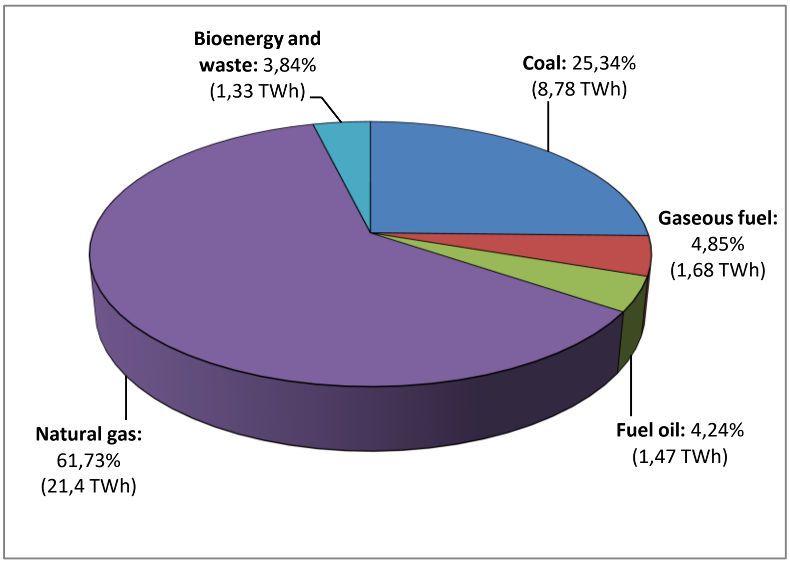

Figure 63. Türkiye Heat Energy Generation by Source, 2020 (MENR, 2020) (based on 34,66 TWh)

According to UNFCCC (United Nations Framework Convention on Climate Change), 2022, GHG emissions arising from electricity and heat production, derived from liquid, solid, gaseous, and other fossil fuels, constitute 92% of the total GHG emissions from the energy industry, amounting to 131.572,78 x 10^6 kg CO_2. The remaining 8% of the GHG emissions in the energy industry arise from petroleum refining, the manufacture of solid fuels, and other energy industries (Table 39). Out of this, 124.256,05 x 10^6 kg CO_2 (94,45%) is attributed to electricity production, and 7.313,78 x 10^6 kg CO_2 (5,55%) is from the emissions generated by heat production.

Table 39. GHG emissions from electricity and heat production (UNFCCC, 2022)

	Emissions from Energy Production			**Global Warming Effects of Emissions**			**Total GHG**
	CO_2	**CH_4**	**N_2O**	**$GWP_{(CO2)}$**	**$GWP_{(CH4)}$**	**$GWP_{(N2O)}$**	
	(10^6 kg)			**(10^6 kg CO_2 eq)**			
Electricity and Heat Production	**(a)**	**(b)**	**(c)**	**(d= a x 1)**	**(e= b x 28)**	**(f= c x 265)**	**(d+e+f)**
Liquid Fuels	414,45	0	0	414,45	0	0	414,45
Solid Fuels	102.468,25	0,73	1,38	102.468,25	20,44	365,7	102.854,39
Gaseous Fuels	27.757,5	0,79	1,37	27.757,5	22,12	363,05	28.142,67
Other Fossil Fuels	130,29	0,03	0	130,29	0,84	0	131,13
Biomass	3.138,38	0,13	0,10	0	3,64	26,5	30,14
Total	133.908,87	1,68	2,85	133.770,49	47,04	755,25	**131.572,78**
a. Electricity Generation							
Liquid Fuels	18,28	0	0	18,28	0	0	18,28
Solid Fuels	100.555,49	0,71	1,36	100.555,49	19,88	360,4	100.935,77
Gaseous Fuels	22.809,01	0,51	1,22	22.809,01	14,28	323,3	23.146,59
Other Fossil Fuels	130,29	0,03	0	130,29	0,84	0	131,13
Biomass	2.514,93	0,11	0,08	0	3,08	21,2	24,28
Total	126.028	1,36	2,66	123.513,07	38,08	704,9	**124.256,05**
b. Combined heat and power generation							
Liquid Fuels	396,16	0	0	396,16	0	0	396,16
Solid Fuels	1.912,75	0,01	0,02	1.912,75	0,28	5,3	1.918,33
Gaseous Fuels	4.948,49	0,28	0,15	4.948,49	7,84	39,75	4.996,08
Other Fossil Fuels	0	0	0	0	0	0	0
Biomass	623,45	0,02	0,01	0	0,56	2,65	3,21
Total	7.880,85	0,31	0,18	7.257,4	8,68	47,7	**7.313,78**

Based on Fig. 62 and Fig 63;

a) Energy Production from fossil sources:

Electrical energy production from fossil sources = 177,066 TWh (Coal, fuel oil, and natural gas)

Heat energy production from fossil sources = 33,33 TWh (Coal, gaseous fuel, fuel oil, and natural gas)

b) Energy Production from renewable energy sources:

Electrical energy production from renewable sources = 129,637 TWh (Renewable energy, bioenergy and waste)

Heat energy production from renewable sources = 1,33 TWh (Bioenergy and waste)

Based on Table 39;

GHG emission from energy from fossil sources:

GHG emission from electrical energy production = 124.256,05 kg CO_2 eq

GHG emission from heat energy production = 7.313,78 kg CO_2 eq

GHG production for 1 kWh of electrical energy production:

GHG production coefficient = GHG from electrical energy production / Electrical energy production

= (124.256,05 x 10^6 kg CO_2 eq) / (306.703 x 10^6 kWh)

= 0,405 kg CO_2 eq/kWh

GHG production for 1 kWh of heat production:

GHG production coefficient = GHG emission/ Heat energy production

= (7.313,78 x 10^6 kg CO_2 eq)/(34.660 x 10^6 kWh)

= 0,211 kg CO_2 eq/kWh

Based on these data, the GHG production coefficient is determined as 0,405 kg CO_2 eq for 1 kWh of electrical energy production and 0,211 kg CO_2 eq for 1 kWh of heat energy production from fossil sources in Türkiye.

GHG values originating from electrical and heat energy production are obtained by multiplying the net avoided energy in Table 39 with the GHG production coefficients for

1 kWh of electrical and heat energy production calculated based on Türkiye energy mix. Total avoided GHG values are calculated by subtracting the GHG values originating from energy production, based on the Türkiye energy production values, from the GHG values of the scenarios in Table 37 (Table 40).

Table 40. Total Avoided GHG Emissions of Basic and Combination Scenarios based on Türkiye energy mix

Scenarios	Net GHG Values of Scenarios	Net Electrical Energy Production	Net Heat Energy Production	GHG from Electrical Energy Production	GHG from Heat Energy Production	GHG from Total Energy Production	Total Avoided GHG
	(kg CO_2 eq)	(kWh)		(kg CO_2 eq)			
	(a)	(b)	(c)	(d = b x 0,405)	(e = c x 0,211)	(f = d + e)	(g = f-a)
B.S-1	908,6	92,2	-	37,3	-	37,3	-871,3
B.S-2	308	537	1.366	217,5	288,2	505,7	197,7
B.S-3	264,9	537	1.366	217,5	288,2	505,7	240,8
B.S-4(a)	354,7	73,4	45,3	29,7	9,5	39,2	-315,5
B.S-4(b)	50,5	298,7	736,9	121	155,5	276,5	226
B.S-5(a)	76,4	181,7	438,7	73,6	92,6	166,2	89,8
B.S-5(b)	58,1	245,6	546,4	99,5	115,3	214,8	156,7
C.S-1	725,8	76,4	-	30,9	-	30,9	-694,9
C.S-2	304,2	210,1	414,8	85,1	87,5	172,6	-131,6
C.S-3	530,6	184,2	341,5	74,6	72	146,6	-384

a: Net GHG values of scenarios (Table 38).

b, c : Avoided electrical and heat energy values of the scenarios..

d: GHG emission of net electrical energy production in the scenarios based on Türkiye's energy balance

e: GHG emission of net heat energy production in the scenarios based on Türkiye's energy balance

f: GHG emission of total energy production in the scenarios based on Türkiye's energy balance

g: Total avoided GHG emission based on Türkiye's energy balance

If the amount of GHG emissions generated from the net heat and electrical energy production in the basic and combination scenarios is compared with the amount of GHG emissions arising from electricity and heat production according to Türkiye's energy mix, only B.S-2, B.S-3, B.S-4(b), B.S-5(a), and B.S-5(b) show avoided GHG emission values. B.S-3 has the highest avoided GHG value at 240,8 kg CO_2 eq, while B.S-4(b) and B.S-2 have the second and third highest avoided GHG values as 226 kg CO_2 eq and 197,7 kg CO_2 eq after B.S-3, respectively.

6.3. LCA (Life Cycle Assessment) Characterization Results of the Scenarios

Based on the LCA methodology using Simapro (see Chapter 4.5.4) the characterization results of LCA impact categories for the basic and combination scenarios are given in Table 41.

Table 41. LCA Characterization Results of Basic and Combination Scenarios

Scenarios	GWP	SOD	FE	TE	PMF	HCT	LU
	(kg CO_2 eq)	(kg CFC-11 eq)	(kg 1,4-DCB)		(kg PM 2,5 eq)	(kg 1,4-DCB)	(m^2a crop area)
B.S-1	956,53	$0{,}36 \times 10^{-4}$	276,66	34,53	-0,091	9,67	1,15
B.S-2	584,78	10×10^{-4}	184,08	34,27	-0,80	9,31	-68,05
B.S-3	487,98	10×10^{-4}	160,95	-94,82	-0,98	-6,63	-69,20
B.S-4(a)	122,72	$-2{,}8 \times 10^{-4}$	121,94	-501,65	-0,59	-14,19	-99,58
B.S-4(b)	46,90	$5{,}4 \times 10^{-4}$	82,06	-427,96	-0,69	-5,57	-112,42
B.S-5(a)	-67,74	$-1{,}6 \times 10^{-4}$	66,95	-551,08	-0,77	-14,22	-119,72
B.S-5(b)	-26,28	$7{,}5 \times 10^{-4}$	74,70	-520,64	-0,91	-9,04	-118,66
C.S-1	651,3	-2×10^{-4}	221,45	-142,09	-0,19	1,44	-31,78
C.S-2	236,81	$4{,}5 \times 10^{-4}$	134,56	-335,17	-0,50	-2,57	-83,74
C.S-3	507,75	$1{,}1 \times 10^{-4}$	190,01	-134,82	-0,20	4,45	-43,40

a) Global Warming Potential (GWP) (kg CO_2 eq)

Basic Scenario-1, which assumes that 1 Mg of MSW is directly sent to the landfill process, has the most negative impact on the GWP category with an emission of 956,53 kg CO_2 eq/Mg waste. C.S-1, which demonstrates the current MSWM of Istanbul, follows this scenario with an emission of 651,3 kg CO_2 eq/Mg emission. Additionally, it is observed that recycling 9,4 kg of metal in the MSW has a positive effect on the GWP, resulting in a GHG saving of 96,8 kg CO_2 eq. B.S-5(a) is the most advantageous scenario in the GWP impact category, followed by B.S-5(b) (Fig. 64).

In the GWP results of Recipe 2016 method, N_2O (nitrous oxide), chlorofluorocarbons, hydrochlorofluorocarbons, hydrofluorocarbons, chlorocarbons, hydrochlorocarbons, bromocarbons, hydrobromocarbons, halons, fluorinated species, and halogenated alcohols and ethers are considered. However, in the GHG calculations in Chapter 6.2, only the global warming effects of CH_4, CO_2, and diesel-oil are considered. Due to this difference in consideration, the GWP results of Simapro are higher than the GHG calculations for all the scenarios based on mass and energy calculations, although the GWP results parallel the GHG calculations.

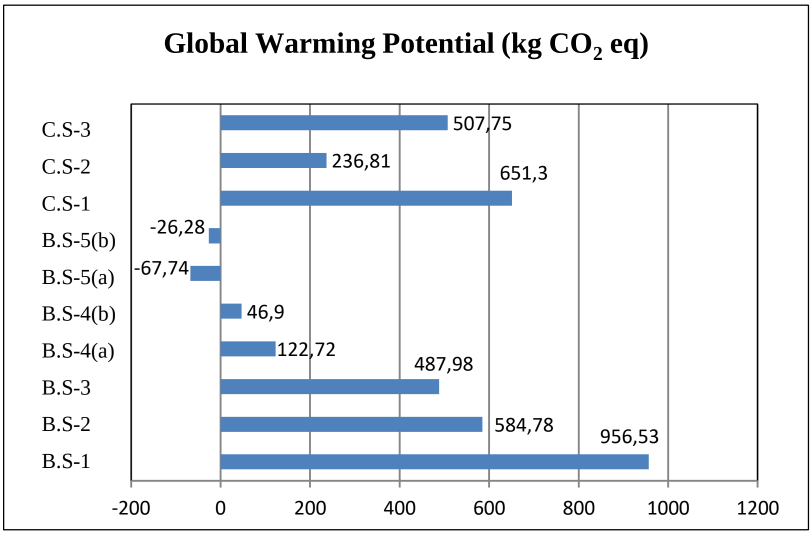

Figure 64. Global Warming Potential of Basic and Combination Scenarios

b) Stratospheric Ozone Depletion (SOD) (kg CFC-11 eq)

B.S-2 (100% of incineration) and B.S-3 (99,06% of incineration + 0,94% of metal recycling) are the worst scenarios in the SOD category, with emission of 10 x 10^{-4} kg CFC-11 eq/Mg. These scenarios are followed by B.S-5(b) with a value of 7,5 x 10^{-4} kg CFC-11 eq/Mg. On the other hand, B.S-4(a) is the best scenario in the SOD impact category, with the maximum avoided emission value of 2,8 x 10^{-4} kg CFC-11 eq/Mg (Fig. 65).

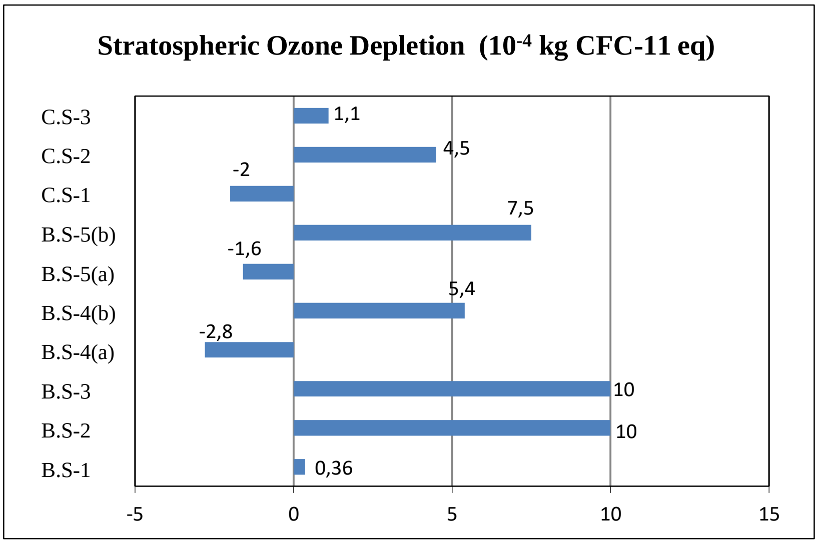

Figure 65. Stratospheric Ozone Depletion Effect of Basic and Combination Scenarios

c) Freshwater Ecotoxicity (FE) (kg 1,4-DCB)

B.S-1 is the worst scenario with the highest freshwater ecotoxicity, having a value of 276,66 kg 1,4-DCB per Mg of the waste. On the other hand, B.S-5(a) and B.S-5(b) are the best scenarios in the FE impact category, with the lowest values of 66,95 kg 1,4-DCB and 74,7 kg 1,4-DCB, respectively (Fig. 66).

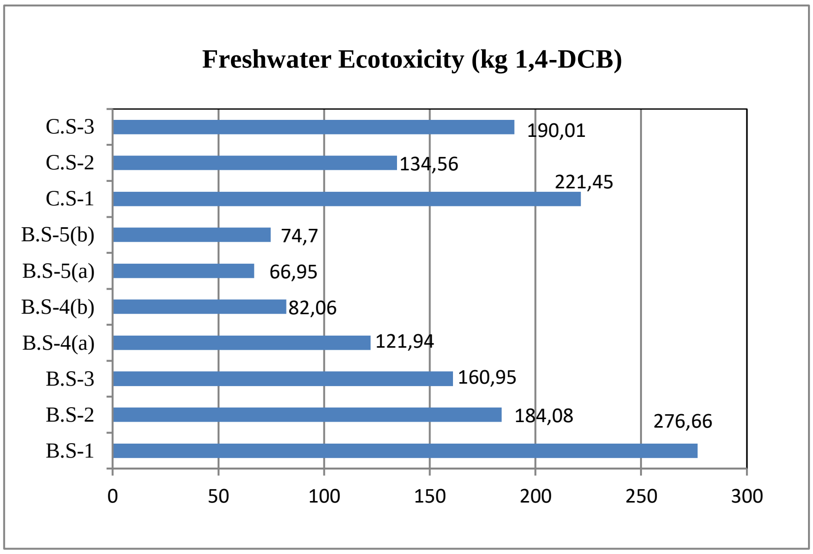

Figure 66. Freshwater Ecotoxicity Effect of Basic and Combination Scenarios

d) Terrestrial Ecotoxicity (TE) (kg 1,4-DCB)

B.S-5(a) and B.S-5(b) are the best scenarios in the TE category, with the highest avoided TE values of 551,08 kg 1,4-DCB and 520,64 kg 1,4-DCB, respectively. On the other hand, B.S-1, where is 1 Mg of MSW is directly sent to the landfill process, and B.S-2, where 1 Mg of MSW is directly sent to the incineration process, are the worst scenarios in this category, with values of 34,53 kg 1,4-DCB and 34,27 kg 1,4-DCB, respectively (Fig. 67).

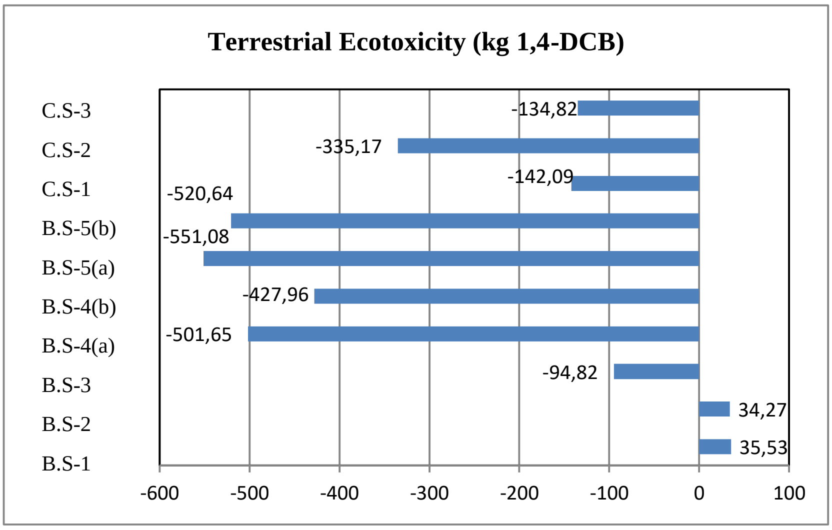

Figure 67. Terrestrial Ecotoxicity Effect of Basic and Combination Scenarios

e) Particulate Matter Formation (PMF) (kg PM 2,5 eq)

In the PMF category, all of the basic and combination scenarios have avoided PMF values (Fig. 68). B.S-1 (100% landfill) and C.S-1 (current MSWM of Istanbul) have the lowest avoided PMF values, with values of 0,091 kg PM 2,5 eq and 0,19 kg PM 2,5 eq, respectively, compared to the other scenarios. The best scenario is B.S-3 (9,4% metal recycling + 99,06% incineration) with an avoided value of 0,98 kg PM 2,5 eq. Furthermore, B.S-5(b) and B.S-5(a) also have higher avoided PMF values of 0,91 kg PM 2,5 eq and 0,77 kg PM 2,5 eq, respectively.

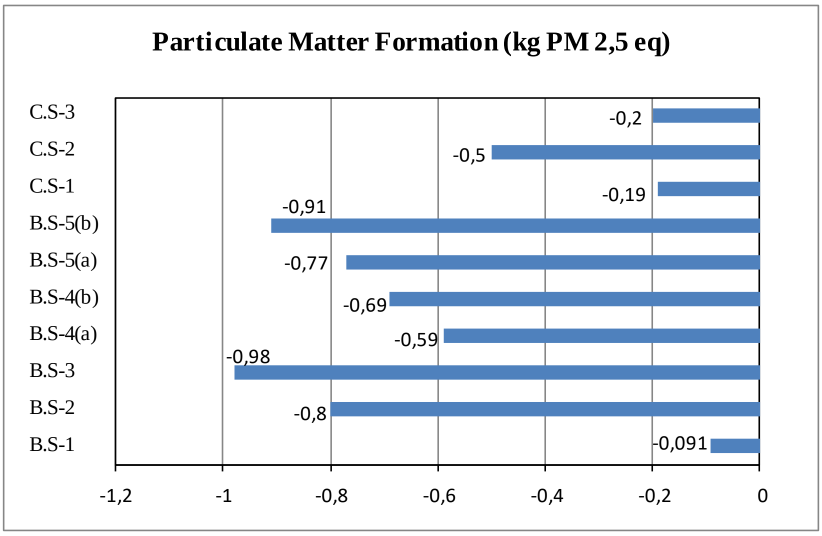

Figure 68. Particulate Matter Formation of Basic and Combination Scenarios

f) Human Carcinogenic Toxicity (HCT) (kg 1,4-DCB)

B.S-5(a) and B.S-4(a) are the best scenarios in the HCT impact category, with avoided HCT values of 14,22 and 14,19 kg 1,4-DCB, respectively. On the other hand, B.S-1 (100% landfill) is the worst scenario, with a value of 9,67 kg 1,4-DCB, and this scenario is followed by B.S-2 (100% incineration) with a value of 9,31 kg 1,4-DCB per Mg of waste (Fig. 69).

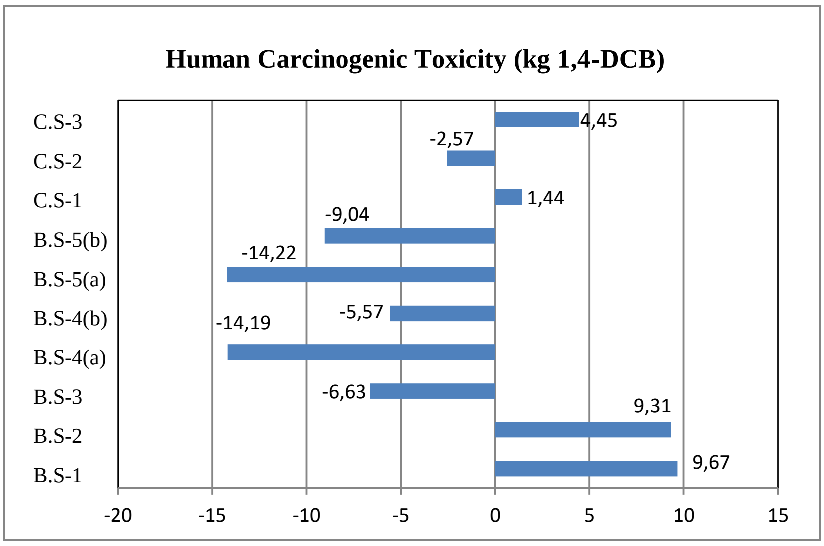

Figure 69. Human Carcinogenic Toxicity of Basic and Combination Scenarios

g) Land Use (LU) (m^2a crop area)

The maximum crop area requirement is in B.S-1 (all the MSW is disposed of with landfill) with a requirement of 1,15 m^2a of crop area per Mg of MSW. All the basic and combination scenarios have avoided land use values, except for B.S-1. This scenario is followed by C.S-1 (current MSWM of Istanbul) with the minimum avoided LU value of 31,78 m^2a of crop area. On the other hand, B.S-5(a) (36,75% composting + 21,15% recycling + 10% landfill + 32,1% incineration) and B.S-5(b) (36,75% anaerobic digestion + 21,15% recycling + 10% landfill + 32,1% incineration) are the best scenarios with the maximum avoided land use values of 119,72 m^2a and 118,66 m^2a of crop areas, respectively, in terms of land use (Fig. 70).

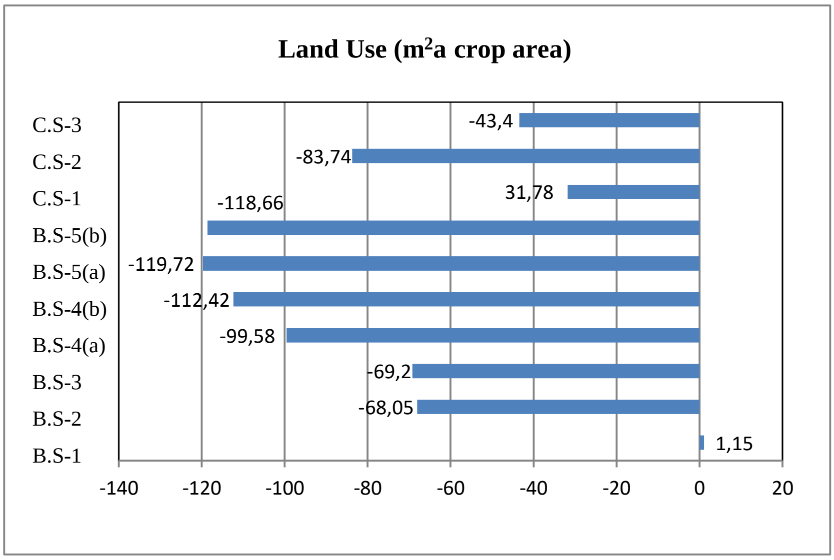

Figure 70. Land Use of Basic and Combination Scenarios

6.4. Results and Discussions of LCA Calculations

A colour-scaled table is used to determine the impact category results of the basic and combination scenarios more clearly. The basic and combination scenarios are arranged from the best scenarios on the left side to the worst scenarios on the right side in Table 42. The best environmental effects results of the scenarios are illustrated with green colours, while the worst results of the scenarios are illustrated with red colours in the table.

Table 42. LCA Environmental Effects of Basic and Combination Scenarios

Impact Categories	The best →									The worst
GWP	B.S-5(a)	B.S-5(b)	B.S-4(b)	B.S-4(a)	C.S-2	B.S-3	C.S-3	B.S-2	C.S-1	B.S-1
SOD	B.S-4(a)	C.S-1	B.S-5(a)	B.S-1	C.S-3	C.S-2	B.S-4(b)	B.S-5(b)	B.S-3	B.S-2
FE	B.S-5(a)	B.S-5(b)	B.S-4(b)	B.S-4(a)	C.S-2	B.S-3	B.S-2	C.S-3	C.S-1	B.S-1
TE	B.S-5(a)	B.S-5(b)	B.S-4(a)	B.S-4(b)	C.S-2	C.S-1	C.S-3	B.S-3	B.S-2	B.S-1
PMF	B.S-3	B.S-5(b)	B.S-2	B.S-5(a)	B.S-4(b)	B.S-4(a)	C.S-2	C.S-3	C.S-1	B.S-1
HCT	B.S-5(a)	B.S-4(a)	B.S-5(b)	B.S-3	B.S-4(b)	C.S-2	C.S-1	C.S-3	B.S-2	B.S-1
LU	B.S-5(a)	B.S-5(b)	B.S-4(b)	B.S-4(a)	C.S-2	B.S-3	B.S-2	C.S-3	C.S-1	B.S-1

GWP

Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are the main greenhouse gases. Landfill process is the major source of CH_4 emissions, whereas incineration, coal, diesel, and natural gas are the main sources of CO_2 fossil emissions (Kaplan, 2009). According to the results of all scenarios, the worst disposal scenario for the GWP impact category is B.S-1, which comprises 100% landfill processes, with a value of 956,53 kg CO_2 eq emissions for 1 Mg of waste, respectively. Landfill process has the highest GWP effect among all processes due to the considerably higher release of CH_4, which has 28 times more GWP than CO_2 emission (IPCC, 2014).

The best scenarios for GWP are B.S-5(a) and B.S-5(b) with avoided GHG emission values of 67,74 kg CO_2 eq and 26,28 kg CO_2 eq values, respectively. In a similar study, Mendes et al. (2004) obtained a value of around 900 kg CO_2 eq/Mg of waste for this impact category in the city of Sao Paulo, Brazil. Miliute and Staniskis (2009) analysed the landfill option for the waste generated in the region of Alytus, Lithuania, and obtained a value of 1.135 kg CO_2 eq/Mg of waste for this impact category. Fernandez-Nava et al. (2014) calculated the GWP value as 4.630 kg CO_2 eq/Mg of waste in the scenario including direct landfill with the recovery of biogas. Gunamantha and Sarto (2012) found a value of 188 kg CO_2 eq/Mg of waste for a similarly defined scenario for three cities in the region of Yogyakarta, Indonesia.

SOD

Biogas arising from landfill is a main contributor to ozone layer depletion, as well as the combustion of diesel, due to emissions of CO, NMVOCs, and VOCs. Therefore, transport activities play a major role in the destruction of the ozone layer (Ripaldi, 2015). The scenarios that have the greatest impact on SOD are B.S-2 (100% incineration) and B.S-3 (99,06% of incineration + 0,94% metal recycling) with values of 10×10^{-4} kg CFC-11 eq/Mg of waste. The most advantageous scenario for SOD is B.S-4(a) with an avoided value of $2{,}8\text{x}10^{-4}$ kg CFC-11 eq. In this scenario, it is assumed that 60% of the total biowaste (approximately 31% of the total waste) is sent to composting and anaerobic processes in half, while 62% of the total recyclable waste (approximately 18,4% of the total waste) is recycled, and 50,6% of the total waste is sent to the landfill process. Similarly, Dastjerdi et al., (2021) showed that the scenario in which all the waste is sent to the incineration process is the worst scenario in the SOD category, while the other scenario in which all the waste is sent to the landfill process has the lowest environmental burden in this impact category.

Hong et al., (2010) investigated ozone layer depletion values of different scenarios and determined these values as $7{,}47\times10^{-6}$ kg CFC-11 eq for landfill, $5{,}73\times10^{-6}$ kg CFC-11 eq for incineration, $8{,}30\times10^{-6}$ kg CFC-11 eq for (composting + landfill), and $4{,}98\times10^{-6}$ kg CFC-11 eq (composting + incineration), respectively. Banar et al., (2009) suggested that the scenario including recycling, composting, and landfilling is the best scenario in the ozone depletion impact category. They also determined that the scenario including recycling and landfilling causes ozone depletion due to methane.

FE

Freshwater ecotoxicity is included because biosolids may be a particular source of toxic compounds, and their use options evaluations need to consider this (Rada, 2016). The impact for this category arises mainly from heavy metal emissions from leachate to water. Areas near landfills have a greater possibility of groundwater contamination because of the potential pollution source of leachate direct mitigation (Ribas, 2015). In this study, B.S-1, which includes 100% of the landfill process, is found to be the most detrimental to the freshwater ecosystem, with a value of 276,66 kg 1,4-DCB. On the other hand, the best scenario for freshwater ecotoxicity is B.S-5(a) with a value of 66,95 kg 1,4-DCB. Ozer and Yay (2021) stated that chromium, mercury, and barium are primary pollutants emitted from electricity consumption during the landfilling processes, causing freshwater, marine, and terrestrial ecotoxicity in Scenario 1, which comprises the landfill process with energy recovery without any source separation.

TE

B.S-1 (100% landfill) and B.S-2 (100% incineration) are the worst scenarios with values of 34,53 kg 1,4-DCB and 34,27 kg 1,4-DCB, respectively in the TE category. Although all the developed scenarios have avoided TE values except for B.S-1 and B.S-2, the most advantageous scenario is B.S-5(a) with an avoided value of 551,08 kg 1,4-DCB in this category. Shekoohiyan et al. (2023) analysed MSWMS for Tehran MSW and found that scenario-4, which includes of all mixed collected MSW sent to incineration, has highest TE value of 2,04 x 10^3 kg 1,4- DCB eq/Mg of waste.

PMF

All of the basic and combination scenarios have avoided PMF values. However, B.S-1 (100% landfill) and C.S-1 (current MSWM of Istanbul) are the most disadvantageous scenarios, which have the lowest avoided PMF values of 0,091 kg PM 2,5 eq and 0,19 kg PM 2,5 eq, respectively. On the other hand, the best scenario is B.S-3 (9,4% metal recycling + 99,06% incineration) with an avoided value of 0,98 kg PM 2,5 eq. B.S-5(b) and B.S-5(a) have the higher avoided PMF values of 0,91 kg PM 2,5 eq and 0,77 kg PM 2,5 eq, respectively compared to the other scenarios. Dastjerdi et al., (2021) used LCA to analyse six scenarios, including different waste disposal options, and they determined that the baseline scenario (landfilling) has the worst effect on the fine particulate matter formation category, while they found that the other scenarios, including incineration and combined waste disposal options, have avoided values in this category.

HCT

HCT results of the scenarios are parallel with TE results. B.S-1 (100% landfill) and B.S-2 (100% incineration) are the worst scenarios with values of 9,67 kg 1,4-DCB and 9,61 kg 1,4-DCB, respectively, while B.S-5(a) and B.S-4(a) are the most favourable scenarios with avoided values of 14,22 kg 1,4-DCB and 14,19 kg 1,4-DCB, respectively, in this impact category. Ogundipe et al., (2015) analysed MSWM in Minna, Nigeria, using LCA tool. They compered four different MSWM scenarios and found that Scenario 2 (82,95% landfilling + 17,95% recycling) and Scenario 3 (82,95% incineration + 17,95% recycling) have the worst effects in the carcinogenic impact category after open dumping option, with the same values of 5,80 x 10^6 kg C_2H_3Cl eq. They also determined that Scenario 4, including approximately 16% recycling + 50% composting + 34% landfill, is the best option in this category.

LU

C.S-1, which reflects the current MSWM situation of Istanbul, is the most space-consuming scenario with a value of 1,15 m^2a crop area/Mg waste. On the other hand, the best scenarios are B.S-5(a) and B.S-5(b) with savings of 119,64 m^2 a crop area and 118,60 m^2 a crop area, respectively. Cherubini et al., (2009) analysed four different scenarios using LCA and determined that the scenarios including landfilling without energy production and landfilling with energy production require the highest areas per 1 Mg of waste, respectively. In the study conducted by Limoodehi et al., (2017) municipal waste in Tehran was assessed according to five suggested scenarios. They suggested that the most appropriate strategy in terms of land usage was Scenario 4 (landfilling + recycling + composting).

Overall Results

Overall, B.S-1 (all of the MSW disposed of in landfill) is the worst scenario in all the impact categories except for SOD. Landfilling has the worst impact on FE and TE categories due to toxic heavy metals migrating from leachate to water and soil. On the other hand, B.S.2 (incineration of the entire waste) has the worst impact on SOD, and it is the second worst impact on the TE and HCT categories due to the formation of PM, SO_2, NO_X, and heavy metals such as Pb, Hg, and Cd.

B.S-5(a) (36,75% composting + 21,15% recycling + 32,1% incineration + 10% landfill) and B.S-5(b) (36,75% anaerobic digestion + 21,15% recycling + 32,1% incineration + 10% landfill) which are developed in line with the EU 2030 waste directive targets, are the best scenarios in all the impact categories, respectively. B.S-5(a) is the most favourable scenario in five out of seven impact categories, including GWP, FE, TE, HCT, and LU, while B.S-5(b) is the second most favourable scenario in five out of seven impact categories, including GWP, FE, TE, PMF, and LU.

C.S-1 (current MSWM of Istanbul) is the worst scenario after B.S-1. This scenario has the second-worst effect in four out of seven impact categories, which are GWP, FE, PMF, and LU. On the one hand, C.S-3 (transition scenario to improve the current MSWM of Istanbul) is determined as the third-worst scenario among all the scenarios, and this scenario has the worst effect in FE, PMF, HCT, and LU. In contrast, C.S-2 (2023 MSWM targets of IMM) has more the best effects in the GWP, FE, PMF, and LU impact categories compared to C.S.1 and C.S-3. Additionally, C.S-2 has avoided impacts in the HCT category, while C.S-1 and C.S-3 have negative impacts.

7. SUMMARY, CONCLUSIONS, AND OUTLOOK

7.1. Summary and Conclusions

Megacities have a significant impact on various living conditions for their citizens. Despite worsening traffic congestion, declining air quality, and increasing health risks, many people choose to reside in these urban centres. Major challenges faced by megacities include climate change, waste management problems, and energy supply issues. Greenhouse gas (GHG) emissions from industries, transportation, and agriculture are likely the primary cause of observed global warming. Waste management presents another substantial challenge for megacities, as they must handle large quantities of waste daily, necessitating extensive logistics for proper disposal.

Moreover, most megacities are situated in emerging countries, which often lack the legal and financial capacity to cope with rapid urban growth. Consequently, organized waste collection and treatment processes may be lacking due to financial constraints. Energy supply poses another problematic issue in megacities. The absence of infrastructure and heavy reliance on fossil fuels, especially in emerging countries, significantly increases air pollutants like GHGs, sulphur, and nitrogen oxides. Therefore, the utilization of energy-efficient technologies that rely on renewable energy sources is crucial to mitigate the negative effects of fossil fuel use while meeting the growing energy demands of the population.

Megacities in particular face the challenge of establishing municipal solid waste management (MSWM) systems that are environmentally sound and meet the goals of climate protection and resource conservation. Therefore, the existing systems and those to be established in the future must be evaluated according to these criteria. For this purpose, Istanbul is used as an example in this thesis.

The challenges of climate change, waste management, and circular economy are prominent in Istanbul, compounding the complexities of handling municipal solid waste. This is particularly resulting from the city's dense population and rapid growth. Istanbul, Türkiye's largest megacity, with a population of 14,8 million people, ranking as the fifth most populous city globally within its limits. The metropolis generates 18.100 Mg of solid waste daily, equivalent to 6.606.500 Mg annually. 83% of the produced MSW disposed of in landfills, while 11% is processed by composting facilities, and 6% of the waste undergoes recycling within the city. These figures underscore the pressing need to address waste disposal methods and to champion recycling and sustainable waste management practices in Istanbul.

This thesis aims to evaluate different MSWM scenarios to determine environmentally the best scenarios for Istanbul megacity, to minimize the negative impacts of the landfill process, to provide an economic sense to waste disposal, and to realize the municipal solid waste strategic targets for Türkiye within the framework the harmonization with EU Green Deal.

The scientific question deals with the investigation and evaluation of the environmental impact of waste management systems in megacities. For the first time, the GHG reductions resulting from waste management measures will be determined for Türkiye, taking into account the energy mix. The specific research questions are:

- What are the environmental effects of the current MSWM system of Istanbul?
- Which MSWM systems can be used to reduce the load of the landfill and environmental burdens?
- With which strategy can 65% of the MSW recycling rate by achieved by 2030.
- Which MSWM systems can reduce the GHG emissions and are preferable to reduce the GHG emissions in the scope of Türkiye's compliance with European Union (EU) Green Deal?
- With which MSWM strategies the goals of EU Waste framework directive can be achieved by 2030?
- What is the best MSWM strategy in terms of climate change, ecosystem quality and human health?

For this the methodologies of mass and energy balances (input-output analyses) based on material flow analyses (MFA) with special consideration of GHG and the methodology of LCA will be applied based on the current MSWM system and alternative waste management scenarios in Istanbul megacity to evaluate different possible MSWM systems. The functional unit is 1 Mg of MSW.

In this context, ten different MSW disposal scenarios are developed under the categories of basic and combination scenarios (including current and planned Istanbul MSW systems):

Basic scenarios

- **B.S-1:** Landfill (1 Mg MSW)
- **B.S-2:** Incineration with energy recovery (1 Mg MSW)
- **B.S-3:** Metal recycling (9,4 kg metal) + incineration with energy recovery (990,6 kg MSW)
- **B.S-4(a):** Recycling (184,5 kg recyclable waste) **+** composting (154,7 kg biowaste) + anaerobic digestion (154,7 kg biowaste) + landfill (506,1 kg residual waste)
- **B.S-4(b):** Recycling (184,5 kg recyclable waste) **+** composting (154,7 kg biowaste) + A.D. (154,7 kg biowaste) + incineration with energy recovery (506,1 kg residual waste)
- **B.S-5(a):** Recycling (211,5 kg recyclable waste) **+** composting (367,5 kg biowaste) + landfill (100 kg residual waste) + incineration with energy recovery (321 kg residual waste)
- **B.S-5(b):** Recycling (211,5 kg recyclable waste) **+** anaerobic digestion (367,5 kg biowaste) + landfill (100 kg residual waste) + incineration with energy recovery (321 kg residual waste)

Combination scenarios

- **C.S-1:** Recycling (60 kg recyclable waste) **+** composting (110 kg biowaste) + landfill (830 kg residual waste)
- **C.S-2:** Recycling (150 kg recyclable waste) **+** anaerobic digestion (250 kg biowaste) + landfill (350 kg residual waste) + incineration with energy recovery (250 kg residual waste)
- **C.S-3:** Recycling (75,3 kg recyclable waste) **+** composting (132,3 kg biowaste) + landfill (542,4 kg residual waste) + incineration with energy recovery (250 kg residual waste)

Firstly, the input and output analysis is conducted by calculating the mass and energy balances of the waste disposal processes and scenarios. The aim is to determine the quantities of waste inputs and outputs, as well as energy inputs and outputs, for each scenario. Here, a differentiation of the material flows is made taking into account the collection rate, sorting rate and the resulting residual waste rate at the level of the collection and defined plant systems and combinations.

In the next step, the net GHG and net energy production values are calculated. This involves assessing the amount of GHG emissions released and the energy generated through waste disposal processes and scenarios. This also takes into account avoided emissions from material recycling.

Following that, Türkiye energy mix is determined, and the GHG production coefficient is calculated for generating 1 kWh of heat and electrical energy. This information is used to calculate the avoided GHG emissions through energy production for each scenario, considering Türkiye's specific energy mix. Finally, all the scenarios are analysed using LCA methodology to determine the most appropriate MSWMS in terms of climate change, ecosystem quality, and human health.

In this context, the current MSWMS of Istanbul is analysed and the Sima Pro software, specifically version 9.3.0.3, is utilized to assess the impacts of the current MSWM practices in the city as well as basic and combination scenarios that have been developed. The analysis focuses on several impact categories, including global warming potential (GWP), stratospheric ozone depletion (SOD), freshwater ecotoxicity (FE), terrestrial ecotoxicity (TE), particulate matter formation (PMF), human carcinogen toxicity (HCT), and land use (LU). The functional unit is selected as 1 Mg of MSW and characterization results are obtained at the midpoint level using the Recipe 2016 Hierarchist (100 years of time horizon) method. These scenarios and the current MSWM of the megacity are analysed to determine the most optimal MSWM option for the metropolitan city of Türkiye.

GHG emission and energy results of the waste treatment processes

Based on the GHG emissions and energy calculations conducted in the inventory analysis, the waste treatment processes have the following results:

Landfilling: The landfilling process releases the highest GHG emissions with a value of 908,6 kg CO_2 eq/Mg waste. However, 92,2 kWh of energy is recovered through the utilization of LFG during the energy production stage in the landfill process.

Incineration: The incineration process follows the landfill process in terms of GHG emission, with a value of 308 kg CO_2 eq/Mg waste. Also, 1.903 kWh of energy is recovered on the energy production stage in the incineration process.

Composting: The composting processes releases 69,9 kg CO_2 eq GHG per Mg of biowaste. Additionally, 48,84 kWh of energy and 13,6 kg CO_2 eq GHG are saved by using 258,4 kg of compost as a fertilizer.

Anaerobic Digestion: The anaerobic digestion process releases 34,6 kg CO_2 eq GHG per Mg of biowaste. 99,25 kWh of energy are recovered and 27,6 kg CO_2 eq GHG are saved by utilizing 525 kg compost (obtained from 670 kg of digestate) as a fertilizer.

Recycling: In addition to the waste disposal processes, recycling of 297,7 kg recyclable waste results in the savings of 187 kg CO_2 eq GHG emissions and 1.404,7 kWh (5.502,82 MJ) energy.

Net GHG and net energy results of the scenarios

Based on the net GHG and net energy production calculations of the scenarios, the worst scenario is B.S-1 (all of the waste is sent to landfill process) with the highest net GHG emission of 908,6 kg CO_2 eq and the lowest net energy value of 92,2 kWh. The second worst scenario is C.S-1 (current MSWM of Istanbul) which exhibits the second highest net GHG emission as 725,8 kg CO_2 eq and the second lowest net energy value as 364,9 kWh . Following B.S-1 and C.S-1, C.S-3 and B.S-4(a) have high net GHG emissions of 530,6 kg CO_2 eq and 354,7 kg CO_2 eq, respectively. Also, C.S-3 has also the third lowest net energy value of 887,5 kWh and B.S-4(a) follows this scenario with 1.012,3 kWh of net energy value.

In contrast, B.S-4(b), B.S-5(b), and B.S-5(a) exhibit the lowest GHG emissions with the values of 50,6 kg CO_2 eq, 58,2 kg CO_2 eq, and 76,5 kg CO_2 eq and the highest net energy values with 1.929,1 kWh, 1.826,4 kWh, and 1.636,4 kWh, respectively. Although B.S-2 (incineration) has the highest net energy value, it has a negative impact on net GHG production calculation. However, when metal recycling is integrated into the incineration process, B.S-3 (metal recycling + incineration) generates the highest net energy value as 2.040 kWh and 264,9 kg CO_2 eq of the lowest net GHG emission after 4(b), 5(a) and 5(b).

Avoided GHG emission of the scenarios based on Türkiye energy mix

According to MENR (2020), 306,703 TWh of electrical energy produced in Türkiye by 2020. Of this total, 34,5% (105,812 TWh) was generated from coal, 0,1% (0,323 TWh) from petrol, 23,13% (70,931 TWh) from natural gas, 1,87% (5,737 TWh) from bioenergy and waste, and 40,04% (123,9 TWh) from renewable energy sources such as wind, geothermal, hydraulic, and solar. Therefore, 57,73% (177,066 TWh) of the electrical energy generated in Türkiye came from fossil sources including coal, petrol, and natural gas.

Additionally, 34,66 TWh of heat energy produced in Türkiye by 2020. Out of this, 25,34% (8,78 TWh) supplied from coal, 4,85% (1,68 TWh) from gaseous fuel, 4,24% (1,47

TWh) from fuel oil, 61,73% (21,4 TWh) from natural gas, and 3,84% (1,33 TWh) from bioenergy and waste. Based on these figures, approximately 93% (33,33 TWh) of the heat energy produced in Türkiye originated from fossil sources which include coal, fuel oil, and natural gas.

Based on the given data, the GHG production coefficient is determined as 0,405 kg CO_2 eq for 1 kWh of electrical energy production and 0,211 kg CO_2 eq for 1 kWh of heat energy production in Türkiye.

When comparing the amount of GHG emissions generated from the net heat and electrical energy production in the basic and combination scenarios with the amount of GHG emissions arising from electricity and heat production according to Türkiye’s energy mix, only B.S-2, B.S-3, B.S-4(b), B.S-5(a) and B.S-5(b) demonstrate avoided GHG emission values.

Among these scenarios, B.S-3 exhibits the highest avoided GHG value of 240,8 kg CO_2 eq, B.S-4(b) and B.S-2 have the second and third highest avoided GHG values as 226 kg CO_2 eq and 197,7 kg CO_2 eq, respectively, following B.S-3. B.S-5(b) follow these scenarios with the avoided 156,7 kg CO_2 eq GHG value while B.S-5(a) has the lowest avoided GHG value as 89,8 kg CO_2 eq.

LCA characterization results of the scenarios

Based on the obtained LCA characterization results at the midpoint level, B.S-1 is the worst scenario among all the scenarios where mixed collected MSW is sent to the landfill processes without any pre-treatment option. This scenario has the most detrimental effect in various impact categories including GWP, FE, TE, HCT, and LU except for SOD with the values of 956,53 kg CO_2 eq, 276,66 kg 1,4-DCB, 34,53 kg 1,4-DCB, 9,67 kg 1,4-DCB and 1,15 m^2a crop area per 1 Mg of the waste, respectively. Furthermore, it has the lowest value with avoided 0,091 kg PM 2,5 eq in PMF impact category among all the scenarios.

On the other hand, B.S-2 has the worst effect on SOD impact category with a value of $10x10^{-4}$ kg CFC-11 eq. It is also the second most detrimental option in TE and HCT impact categories, with amounts of 34,27 kg 1,4-DCB and 9,31 kg 1,4-DCB, respectively. On the other hand, B.S-3 is the most advantageous scenario in the PMF category with the avoided 0,98 kg PM 2,5 eq. This scenario has the reasonable effect in HCT impact category.

B.S-5(a) is considered the best scenario among all the scenarios. In this scenario, 71,25% of the total biowaste (equivalent to 36,75% of the total waste) is sent to composting processes, 71,45% of the total recyclable waste (equivalent to 21,15% of the total waste) is recycled and 32,1% of the total waste is sent to the incineration process with only 10% of the total waste going to the landfill. B.S-5(a) is determined to be the most favourable option in five out of the seven impact categories. It has the highest avoided values of 67,74 kg CO_2 eq, 551,08 kg 1,4-DCB, 14,22 kg 1,4-DCB and 119,72 m^2a crop area in GWP, TE, HCT, and LU impact categories, respectively. It also has the lowest detrimental effect in FE impact category with 66,95 kg 1,4-DCB among all the scenarios.

B.S-5(b) has the second best effect in GWP, FE, TE, PMF, and LU impact categories. This scenario has the highest avoided values of 26,28 kg CO_2 eq, 520,64 kg 1,4-DCB, 0,91 kg PM 2,5 eq, and 118,66 m^2a crop area, respectively in GWP, TE, PMF, and LU impact categories. It also has the second lowest detrimental effect in FE impact category with 74,7 kg 1,4-DCB among all the scenarios.

B.S-4(a) and B.S-4(b) represent the subsequent best scenarios after B.S-5(a) and B.S-5(b), respectively. Among these scenarios, B.S-4(a) demonstrates the most favourable impact on SOD with the avoided $2,8 \times 10^{-4}$ kg CFC-11 eq value, the second-most favourable impact on HCT with the avoided 14,19 kg 1,4-DCB, and the third-most favourable impact on TE impact category with the avoided 501,65 kg 1,4-DCB. It exhibits reasonable effects on the remaining impact categories as well. Meanwhile, B.S-4(b) has the third-best effect in GWP, FE, and LU impact categories with the values of 46,9 kg CO_2 eq, 82,06 kg 1,4-DCB, and the avoided 112,42 m^2a crop area, respectively. This scenario has also reasonable effects in the remaining impact categories. As for C.S-2, it also has the reasonable effects in all impact categories.

It is evident that the current MSWM in Istanbul, as represented by C.S-1 (6% recycling + 11% composting + 83% landfill), ranks as the second-worst scenario in the terms of GWP, FE, PMF, and LU categories following B.S-1. This is mainly due to the high percentage of MSW being landfilled. It has 651,3 kg CO_2 eq value in GWP, 221,45 kg 1,4-DCB value in FE, and the second lowest avoided values of 0,19 kg PM 2,5 eq and 31,78 m^2a crop areas in PMF and LU impact categories, respectively. However, C.S-1 is the second-best option only in the SOD impact category with the avoided value of 2×10^{-4} kg CFC-11 eq. C.S-2 (15% recycling + 25% anaerobic digestion + 25% incineration + 35% landfill) which is developed based on the 2023 MSWM targets of IMM demonstrates reasonable effects in all the impact categories. C.S-3 (7,53% recycling + 13,23% composting + 25% incineration + 54,24%

landfill) represents a transitional scenario that incorporates realistic percentages of MSW disposal methods applicable to Istanbul in order to achieve 50% of the recycling and landfill targets set by the EU for 2030. Similarly, C.S-3 (7,53% recycling + 13,23% composting + 25% incineration + 54,24% landfill) is not an optimal option, which include 2023 MSWM targets of IMM. This scenario has the worst effect in FE, PMF, and LU impact categories, following B.S-1 and C.S-1. It has 134,56 kg 1,4-DCB value in FE and the lowest avoided values of 0,20 kg PM 2,5 eq and 43,4 m^2a crop areas in PMF and LU impact categories, respectively. Furthermore, it has the third most detrimental impact on the HCT category with the value of 4,45 kg 1,4-DCB

Overall Results

The disposal of the mixed collected MSW through the landfill process without any source separation option (B.S-1) has the most detrimental impact on all the impact categories, including GWP, FE, TE, PMF, HCT, and LU except for SOD. This is primarily due to the higher proportion of direct CH_4 emission and leachate generation associated with this process. B.S-1 also has the lowest net energy production and does not contribute to avoided energy based on Türkiye energy mix.

While incineration of mixed collected MSW has the highest avoided energy value among all waste disposal options, the application of only incineration process (B.S-2) is considered the worst scenario in the SOD category and the second-worst scenario in TE and HCT. Furthermore, it ranks as the third-worst scenario in terms of the GWP category. However, by incorporating metal recycling into the incineration plant (B.S-3), specifically, there is a reduction of 96,8 kg CO_2 eq in GWP, 23,13 kg 1,4-DCB in FE, 129,1 kg 1,4-DCB in TE and 15,94 kg 1,4-DCB in HCT with through the recycling of 9,4 kg of metal. Additionally, there is an increase of 0,18 kg PM 2,5 eq in the avoided PMF value and an increase of 1,15 m^2a crop area in the LU category.

Composting process is considered the most favourable waste treatment method when compared to anaerobic digestion, primarily due to its lower impacts in various categories GWP, SOD, PMF, TE, FE and LU except for PMF category. The energy production potential of anaerobic digestion is generally higher compared to the composting process. Therefore, the choice between composting and anaerobic digestion would depend on the specific objectives and priorities, taking into account both the environmental impacts and energy production aspects.

Increasing separate collection and recycling rates have a significant mitigating effect on the unfavourable impacts in all impacts categories. This is primarily due to the higher amount of avoided energy and GHG emissions associated with recycling efforts. Based on the inventory analysis calculation, it is found that 187 kg CO_2 eq of GHG and 1.404,7 kWh of energy are saved as a result of recycling a total of 297,7 kg of recyclable waste, these values correspond to avoided 0,63 kg CO_2 eq of GHG and 4,72 kWh of energy per kg of recycled waste (glass, plastic, paper-cardboard, metal, and electric-electronic waste). According to LCA calculation results, on the unfavourable impacts in all impacts categories, there is 10,3 kg CO_2 eq avoided value in GWP, 2,5 kg 1,4-DCB avoided value in FE, 13,7 kg 1,4-DCB avoided value in TE, 0,02 kg PM 2,5 eq avoided value in PMF, 1,7 kg 1,4-DCB avoided value in HCT, and avoided 0,12 m^2a crop area in LU impact categories with the recycling of 1 kg of the metal.

In conclusion, C.S-1 (Current MSWMS of Istanbul) ranks as the second-worst scenario, following B.S-1 after the conducting GHG and energy production analysis, as well as LCA calculations. The unfavourable impacts observed in terms of GHG emissions and energy production emphasized the necessity for improvements in the waste management system.

Among the scenarios evaluated, C.S-3 (7,53% recycling + 13,23% composting + 25% incineration + 54,24% landfill) is identified as the most applicable scenario for Istanbul for realisation in short time. This scenario can be implemented immediately as a transition strategy to meet 50% of the recycling and landfill targets set by the EU for 2030. By adopting C.S-3, the amount of waste sent to landfills can be significantly reduced, leading to a decrease in the negative impacts such as GWP, FE, TE, PMF, HCT, and LU associated with landfilling practices. Implementing C.S-3 would support the reduction of landfilled waste, promote recycling and composting efforts, and contribute to a more sustainable waste management system in Istanbul.

Although B.S-5(a) and B.S-5(b) are the best scenarios among all the scenarios the implementation of these scenarios is not actually possible in megacities located in emerging countries such as Türkiye in a short time. Significant investments in collection systems and plant technologies are required to achieve the high rates for recycling and energy recovery. Citizens must be involved in the separate collection systems through intensive public relations work. The legal framework and enforcement to achieve the goals are a necessary prerequisite.

In this context, the implementation of B.S-4(b) scenario would be easier for Istanbul and other megacities located in emerging countries. The separation of waste as into dry and wet waste at the source would facilitate the source reduction process easy, thereby increasing the efficiency of recycling/recovery processes. The load on the landfills would be reduced source separation and disposal of biowaste through biological process would help reduce greenhouse gas production and achieve reduce and resource and energy savings. Additionally the implementation of B.S-4(b) would result in avoided GHG emissions from energy production based on Türkiye energy mix. The implementation of this scenario would make it possible to achieve the targets of the EU Waste Directive in the harmonization process, meet the country's solid waste management objectives to reach international standards and minimize environmental impacts.

In conclusion, it has been determined that the stand-alone application of landfill or incineration without any recycling and pre-treatment option do not meet the target of sustainable MSW management. On the other hand, a combination of 36,75% composting, 21,15% recycling, 32,1% incineration processes, and 10% of landfill process is found to be the preferred and best options in the case of Istanbul.

Furthermore, the implementation of anaerobic digestion and incineration process can help reduce external energy dependency. These processes have higher potential for renewable energy generation compared to landfill. By utilizing anaerobic digestion and incineration, energy savings can be achieved, as well as a reduction in CH_4 and CO_2 emissions. Anaerobic digestion, which involves the breakdown of organic waste in the absence of oxygen, produces biogas that can be used as a renewable energy source. This process not only generates energy but also helps mitigate CH_4 emissions, as organic waste in landfills is a significant source of methane production. Similarly, incineration of waste can generate heat or electricity through the combustion of waste materials. This process contributes to renewable energy generation, reduces the need for fossil fuels, and helps mitigate CO_2 emissions. By implementing anaerobic digestion and incineration processes, countries can enhance their energy independence, decrease reliance on foreign energy sources, and contribute to environmental sustainability by reducing greenhouse gas emissions.

Given the scope of this thesis, the scientific results can to serve as a valuable reference for future studies on solid waste management in megacities. The insights and findings presented in this thesis will contribute to advancing our understanding of sustainable waste management practices in the context of rapidly growing urban areas.

7.2. Outlook

In this thesis, only MSW treatment processes are evaluated, collection and transportation stages of MSWM options are not taking into account. Furthermore, the evaluation of MSWM alternatives is conducted solely from an environmental perspective. However, it is important to support this analysis with other decision-making tools that take into account the economic and social effects of solid waste management.

Future investments in waste management systems should involve holistic evaluations that incorporate not only the key social benefits and costs of energy generation but also consider emissions reductions, impacts on public health, and identification of necessary policy support to ensure viable and sustainable solutions. For this reason, it is crucial that the future of MSWM systems be financially sustainable in addition to being environmentally and socially acceptable.

Future research work should address the following research questions related to the MSWM in a megacity:

- What are the environmental effects of the collection and transporting of MSWM in megacities, and how can these impacts be minimized?
- How to rapidly changing spatial, economic, and social conditions affect MSWM systems in megacities? What strategies are needed to establish sustainable systems?

This offers the opportunity to develop and implement MSWM in megacities in a more environmentally sound, socially acceptable, and economically feasible manner in the future. Megacities in particular face the challenge of establishing municipal solid waste management (MSWM) systems that are environmentally sound and meet the goals of climate protection and resource conservation. Therefore, the existing systems and those to be established in the future must be evaluated according to these criteria.

REFERENCES

Adhikari, B., Dahal, K.R., Khanal, S.N., 2014. Review of Factors Affecting the Composition of Municipal Solid Waste Landfill Leachate, International Journal of Engineering Science and Innovative Technology (IJESIT) 3(5):273.

Allevi, E., Gnudi, A., Konnov, I., V., and Oggioni, G., 2021. ‘Municipal Solid Waste Management in Circular Economy: A Sequential Optimization Model. Energy Economics, Volume: 100, August 2021, 105283.

Al Qattan, N., Acheampong, M., Jaward, F.M., Ertem, F.C., Vijayakumar, N., Bello, 2018. ‘Reviewing the Potential of Waste-to-Energy (WTE) Technologies for Sustainable Development Goal (SDG) Numbers Seven and Eleven, December 2018. Renewable Energy Focus, Volume 27, Pages 97-110.

Angelo, A. C. M., Saraiva, A. B., Climaco, J. C. N., Infante, C. E., Valle, R., 2016. ‘Life Cycle Assessment and Multi-criteria Decision Analysis: Selection of a strategy for domestic food waste management in Rio de Janeiro.’ Journal of Cleaner Production: 1-13.

Bagchi, A., 2004. ‘Design of landfills and integrated solid waste management’ John Wiley and Sons Inc., Hoboken, NJ.

Banar, M., Cokaygil, Z., Ozkan, A., 2009. Life cycle assessment of solid waste management Options for Eskisehir, Turkey Waste Management 29: 54–62

Berkun, M., Aras, E., Anılan, T., 2011. ‘Solid Waste Management Practices in Turkey.’ Journal of Material Cycles and Waste Management 13,305–313.

Beyene, H., D., Werkneh, A., A., Ambaye, T., G., 2018. ‘Current Updates on Waste to Energy (WtE) Technologies: A Review. Renewable Energy Focus, Volume:24, Pages:1-11, March 2018, Research Review.

BMU (Bundesministerium für Umwelt, Naturschutz und Nukleare Sicherheit), 2018. Waste Management in Germany: Facts, data, diagrams. BMU, Division WR II 1, Dr Andreas Jaron, Christina Kossmann.
https://www.bmu.de/fileadmin/Daten_BMU/Pools/Broschueren/abfallwirtschaft_2018_en_bf.pdf

Bohra, A., Nema, A. K., Ahluwalia, P., 2012. 'Global Warming Potential of Waste Management Options: Case Study of Delhi.' Int. J. Environmental Technology and Management. Vol: 15, 3/4/5/6.

Borrion, Li, A., Khraisheh, M., Benyahia, F., 2012. Environmental life cycle impact assessment of Gas-to-Liquid processes, Proceedings of the 3rd Gas Processing Symposium, Volume 3 in Advances in Gas Processing, 71-77,434.

Boskovic G, Jovicic N, Jovanovic S, Simovic V. Calculating the costs of waste collection: A methodological proposal. Waste Management & Research. 2016; 34(8): 775-783.

Buchholz, R., Paton-Walsh, C., Griffith, D., Kubistin, D., Caldow, C., Fisher, J., 2016. Source and meteorological influences on air quality (CO, CH_4 & CO_2) at a Southern Hemisphere urban site, Atmos. Environ., 274-289.

Buvet, R., Fox, M.F., Picken, D., J., 1980. 2 Biomethane Production and Uses. Turret Wheatland Ltd. ISBN: 0-901808-22-9.

Cetinkaya, A. Y., Bilgili, L., Kuzu, S. L., 2018. 'Life Cycle Assessment and Greenhouse Gas Emission Evaluation from Aksaray Solid Waste Disposal Facility.' Air Quality Atmosphere and Health. 11:549-558.

Cencic, O., and Rechberger, H., 2008. 'Material Flow Analysis with Software STAN.' Environmental Informatics and Industrial Ecology Copyright © Shaker Verlag, Aachen 2008. ISBN: 978-3-8322-7313-2. Enviro. Info. 2008 (Lüneburg).

Chen, S., Huang, J., Xiao, T., Gao, J., Bai, J., Luo, W., Dong, B., 2020. 'Carbon Emissions under Different Domestic Waste Treatment Modes Induced by Garbage Classification: Case Study in Pilot Communities in Shanghai, China.' Waste Management, 717: 137193.

Chensi, Q., Jinru, B., Lin, B., and Xi L., 2019. 'Solid Waste Management-Briefing on China Green Development.' Europe-China Eco-Cities Link, December 2019, Beijing.

Cherubini, F., Bargigli, S., and Ulgiati, S., 2009. 'Life Cycle Assessment (LCA) of Waste Management Strategies: Landfilling, Sorting Plant and Incineration. Energy, Volume 34, Issue 12, December 2009, Pages: 2116-2123.

Cleaner Production, 2023. 'Waste Treatment and Material Processing, Mechanical-Biological Waste Treatment/Stabilisation', Umwelt Bundesamt. Accessed: 3.02.2023. https://www.cleanerproduction.de/images/BestPractice/data_en/MBT.pdf

Consonni, S., Giuglianob, M., Grossob, M., 2005. 'Alternative strategies for energy recovery from municipal solid waste' Part A: Mass and energy balances. Waste Management, Volume 25, Issue 2, 2005, 123-135.

Dašić, P., 2007. Analysis and evaluation of software tools for life cycle assessment, Annals of the University of Petrosani, Electrical Engineering, 9, 6-15.

Dastjerdi, B., Strezov, V., Kumar, R., He, J., Behnia, M., 2021. 'Comparative life cycle assessment of system solution scenarios for residual municipal solid waste management in NSW, Australia.' Science of the Total Environment, Volume:767, 1 May 2021, 144355.

Daura, L., A., 2016. 'Determination of Greenhouse gas emission from incineration of municipal solid waste in Kano, Nigeria.' International Journal of Scientific & Engineering Research, Volume 7, Issue 7. ISSN 2229-5518.

Demirer G. N., 2011a. Yasam Döngüsü Analizi, Sürdürülebilir Üretim ve Tüketim Yayınları, Bölgesel Çevre Merkezi- REC Türkiye, ISBN: 978-975-6180-42-6. http://www.rec.org.tr/dyn_files/20/5928-I-YASAM-DONGUSU-ANALIZI.pdf.

Dolgen, D., Sarptas, H., Alpaslan, N., Kucukgul, O., 2005. Energy Potential of Municipal Solid Wastes Energy Potential of Municipal Solid Wastes, Energy Sources, 27:15, 1483-1492, DOI: 10.1080/009083190523820.

EC (European Commission), 2020. 'Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the regions. A new Circular Economy Action Plan for a Cleaner and More Competitive Europe. The European Green Deal.' 2020/98/EC. Accessed: 13.05.2022
EUR-Lex - 52020DC0098 - EN - EUR-Lex (europa.eu)

EC, 2018b, Market study on date marking and other information provided on food labels and food waste prevention, Annexes to Final Report. Directorate-General for Health and Food Safety, January 2018.
https://food.ec.europa.eu/system/files/2018-07/fw_lib_srp_date-marking_sum_annexes.pdf
Accessed: 03.02.2023.

EC (European Commission), 2015. Directive of the European Parliament and of the Council. Amending Directive 2008/98/EC on Waste, 2015/0275 (COD).

EC (European Commission), Directive 2008/98/EC on waste (Waste Framework Directive)
https://ec.europa.eu/environment/waste/framework/ Accessed: 16.10.2022

EC (European Commission), 1999. Council Directive 1999/31/EC of 26 April 1999 on the Landfill of Waste. Official Journal European Communities L 182/1, 16/7/1999.

Economopoulos A. P., (2009). "Techno economic aspects of alternative municipal solid wastes treatment methods." Waste Management, Volume 30, Issue 4, 707-715.

EEA, 2020. European environment agency, Bio-waste in Europe- Turning Challenges into Opportunities. EEA Report, No: 04/2020. ISSN: 1977-8449.

EEA, 2019. European environment agency, 'Ozone-depleting substances 2019.' Report No: 12/2019. ISSN 1977-8449.

Eisted, R., Larsen, A. W., Christensen, T.H., 2009. Collection, transfer and transport of waste: accounting of greenhouse gases and global warming contribution. Waste Management& Res. 27: 738–745.

EMF, 2015a, 'Circular economy overview' http://www.ellenmacarthurfoundation.org/circular-economy/overview/concept Accessed: 05.11.2015.

EPA, S.A. (Environment Protection Authority, South Australia), 2019. Waste Guidelines, Waste Definitions. https://www.epa.sa.gov.au/files/4771336_guide_waste_definitions.pdf

EPEM (Environmental Planning Engineering and Management), 2020. Waste-C-Control, Database of Waste Management Technologies, Composting 3: Tunnel Composting. http://www.epem.gr/waste-c-control/database/default.htm Accessed: 20.03.2020

Eriksson, O., Carlsson-Reich, M., Frostell, B., Björklund, A., Assefa, G., Sundqvist, J.O., Granath, J., Baky, A. And Thyseliuz, L., 2005. 'Municipal Solid Waste Management from a System Perspective.' Journal of Cleaner Production, Vol. 13, Issue 3: 241-252.

Ermolaeva, Y. V., Weins, N. W., Silva, C. L. da and Ferreira, L., 2019. 'Social factors of waste management in megacities: a comparison between Moscow & São Paulo.' Conference: 10º Forum Internacional de Resíduos Sólidos at: João Pessoa. Project: Public Policy and Dynamics of Territorial Development, June 19.

Escalante, N., Rymkiewicz, A., Kranert, M., 2010. 'Understanding Waste Management in a Megacity - Experiences in Addis Ababa, Ethiopia.' Report, University of Stuttgart.

EEA (European Environment Agency), 1997. 'Life Cycle Assessment (LCA).' A guide to approaches, experiences and information sources. Environmental Issues Series, No.6.

Eurostat, 2020. 'Municipal Solid Waste Statistics-Statistics Explained.' https://ec.europa.eu/eurostat/statistics-explained/pdfscache/10360.pdf

Fernandez-Nava Y, del Río J, Rodríguez-Iglesias J, Castrillón L, Marañón E., 2014. 'Life cycle assessment of different municipal solid waste management options: A case study of Asturias (Spain).' J Clean Prod 2014; 81:178–89.

Ferronato, N., Torretta, V., 2019. Waste Management in Developing Countries: A Review of Global Issues, Int J Environ. Res. Public Health. Mar; 16(6): 1060.

Gajalakshmi, S., Abbasi, S. A., 2008. Solid Waste Management by Composting: State of the Art, Critical Reviews in Environmental Science and Technology 38(5):311-400.

Garfì, M., Bonoli, A., 2009. Waste Disposal In Developing Countries And Emergency Situations. The Case Of Saharawi Refugees Camps. DICMA, University of Bologna.

Goren, S. and Ozdemir, F., 2010. Regulation of waste and waste management in Turkey, Waste Management & Research 29(4) 433–441.

GHG Protocol, 2013. 'Protocol for the Quantification of Greenhouse Gas Emissions from Waste Management Activities.' Version 5.0. EPE (Entreprises pour l'Environnement) https://ghgprotocol.org/sites/default/files/Waste%20Sector%20GHG%20Protocol_Version%205_October%202013_1_0.pdf

Gunamantha, M., Sarto, 2012. 'Life cycle assessment of municipal solid waste treatment to energy options: Case study of Kartamantul region, Yogyakarta.' Renewable Energy 41, 277–284.

Gursel, A. P., Maryman, H., Ostertag, C., 2016. 'A life-cycle approach to environmental mechanical and durability properties of "green" concrete mixes with rice husk ash.' Journal of Cleaner Production, 112: 823-836.

Gunduzalp, A. A., Guven, S., 2016. 'Waste and Waste Types, Waste Management, Recycling and Consumer: Cankaya Municipality and Instance of Neighbourhood Consumers.

Guven, H., Wang, Z., Eriksson, O., 2019. 'Evaluation of future food waste management alternatives in Istanbul from the life cycle assessment perspective.' Journal of Cleaner Production, Volume: 239, 1 December 2019, 117999.

Harris, 2020. G. James Harris, MPA. 'Megacities, Micro haulers and Food Waste: Lessons from New York. https://www.linkedin.com/pulse/megacities-microhaulers-food-waste-lessons-from-new-york-harris?trk=portfolio_article-card_title Accessed: 02.02.2023.

He J, Yu Z, Fukuda H., 2021. 'Extended Theory of Planned Behaviour for Predicting the Willingness to Pay for Municipal Solid Waste Management in Beijing. Sustainability.' 2021; 13(24):13902.

Heimlich, J. E., Hughes, K. L. and Christy A. D., 2007. 'Integrated Solid Waste Management.' Ohio State University (OSU) Extension Fact Sheet CDFS-106-05.

Hong, J., Li, X., Zhaojie, C., 2010. 'Life cycle assessment of four municipal solid waste management scenarios in China.' Waste Management 30:2362–2369.

Humbert, 2012. Humber, S., Schryver, A. D., Bengoa, X., Margni, M., and Jolliet, O. 'IMPACT 2002+: User Guide, Draft for version Q2.21 (version adapted by Quantis, November 1, 2012.

IEA (International Environmental Agency), 2001. Biogas and more: Systems and Markets Overview of Anaerobic digestion Retrieved on 14 June 2006.

Ifu Hamburg GmbH, Umberto LCA Software www.umberto.de Accessed: 28.01.2021.

IMM (Istanbul Metropolitan Municipality), 2020. Solid Waste Transfer Stations. Environmental Protection and Control Department, Waste Management Directorate. https://cevre.ibb.istanbul/atik-yonetimi-mudurlugu-sube-mudurlugu/kati-atik-aktarma-istasyonlari/ Accessed: 03.06.2020.

IPCC (International Panel on Climate Change), 2014. Climate Change 2014: Synthesis Report. Edited by the Core Writing Team (Synthesis Report IPCC), Pachauri R., K., (Chairman IPCC), and Meyer L. (Head, Technical Support Unit IPCC). ISBN: 978-92-9169-143-2.

IPCC (International Panel on Climate Change), 2007. Forster P, Ramaswamy V, Artaxo P, Berntsen T, Betts R, Fahey DW, Haywood J, Lean J, Lowe DC, Myhre G, Nganga J, Prinn R, Raga G, Schulz M, Van Dorland R. Chapter 2: Changes in atmospheric constituents and in radiative forcing. In: Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, New York, USA.

IPCC (International Panel on Climate Change), 2006. Guidelines for national greenhouse gas inventories. 2013-04-28 Volume: 5. IPCC National Greenhouse Gas Inventory Program; IPCC, WMO, Geneva, Switzerland.

IPCC (Integrated Pollution Prevention and Control) BREF, 2006. European Commission, Integrated Pollution Prevention and Control – Reference Document on the Best Available Techniques for Waste Treatment Industries.

IPCC (International Panel on Climate Change), 2001. Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T., et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881 pp.

IPCC (International Panel on Climate Change), 1996. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories. Reference manual.

Ireland's National Waste Policy, 2020. 'A Waste Action Plan for a Circular Economy' Ireland's National Waste Policy, 2020-2022. Prepared by the Department of Communications, Climate Action and Environment, Government of Ireland.

ISO (International Standard Organization) 14044, 2006. Environmental Management – Life Cycle Assessment – Requirements and Guidelines. International Organization of Standardization.

ISO (International Standards Organization) 14040, 1997. Environmental Management - Life Cycle Assessment - Principles and Framework.

ISTAC (Istanbul Environmental Management Industry and Trade Incorporated Company), 2020. 'Istanbul Municipal Solid Waste Disposal Processes' and 'Current Municipal Solid Waste Management Diagram' (Personal Interview, 06.07.2021).

ISTAC (Istanbul Environmental Management Industry and Trade Incorporated Company), 2019. Istanbul Metropolitan Municipality, Waste Incineration and Energy Production Facility, Definition and Purpose of the Project. Accessed: 04.09.2019.

ISTAC (Istanbul Environmental Management Industry and Trade Incorporated Company), 2019. 'Kemerburgaz Recovery and Composting Plant Flow Diagram' and 'Kemerburgaz Recovery and Composting Plant Mass Balance'. Accessed: 11.01.2019.

ISTAC, (Istanbul Environmental Management Industry and Trade Incorporated Company), Annual Report 2018. https://istac.istanbul/tr/hakkimizda/raporlar Accessed: 20.01.2019

ISTAC (Istanbul Environmental Management Industry and Trade Incorporated Company), 2018. 'Istanbul Municipal Solid Waste Characterization, Composition Data by 2018' and 'Istanbul Municipal Solid Waste Elemental Analysis Value by 2018'. Accessed: 11.01.2019.

ISTAC, (Istanbul Environmental Management Industry and Trade Incorporated Company), Annual Report 2017. https://istac.istanbul/tr/hakkimizda/raporlar Accessed: 12.12.2018.

ISTAC (Istanbul Environmental Management Industry and Trade Incorporated Company), 2017. Odayeri Landfill Database: 'Amount of Landfilled Waste, Leachate Generation, Landfill Gas Generation, Electricity Consumption and Generation, Diesel Consumption'. Accessed: 18.01.2019

Istanbul CCAP, 2021. Istanbul Climate Change Action Plant (CCAP) 2021, Chapter 2: GHG Emissions, Inventory, and Pathways. Istanbul Metropolitan Municipality, Department of Environmental Protection and Development.

ISWA, 2020. Jurgensen, M., R., Gilbert, J., and Ramola, A. 'Global Assessment of Municipal Organics.' Biocycle, AD & Biogas, Composting, March 24 2020. The International Solid Waste Association's Working Group on the Biological Treatment of Waste Released the Global Assessment of Municipal Organic Waste Production and Recycling. https://www.biocycle.net/iswa-global-assessment-municipal-organics/ Accessed: 23.10.2022.

Jha, K. A., Sharma, C., Singh, N., Ramesh, R., Purvaja, R., Gupta, P. K., 2008. 'Greenhouse gas emissions from municipal solid waste management in Indian mega-cities: A case study of Chennai landfill sites.' Journal & Books, Chemosphere, Volume: 71, Issue: 4, Pages: 750-758.

Johnke, B., (1999). 'Emissions from waste incineration.' Background paper for Expert meeting on good practice in inventory preparation: Emissions from waste. IPCC/OECD/IEA National Greenhouse Gas Inventories Programme, (Unpublished – TSU, Japan).

Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G., Rosenbaum, R., (2003) IMPACT 2002+: a new life cycle impact assessment methodology. Int J Life Cycle Assess 8:324–330.

JRC (Joint Research Centre) Institute for Environment and Sustainability, 2011. 'Supporting Environmentally Sound Decisions for Bio-Waste Management.' JRC-IES, 2011. European Commission-Joint Research Centre — Institute for Environment and Sustainability: International Reference Life Cycle Data System (ILCD) Handbook — Recommendations for Life Cycle Impact Assessment in the European context. First edition November 2011. EUR 24571 EN. Publications Office of the European Union, Luxemburg.

Juárez-Hernández, S., 2021. 'Energy, Environmental, Resource Recovery, and Economic Dimensions of Municipal Solid Waste Management Paths in Mexico City.' Waste Management, Volume: 136, Pages 321-336.

Jürgensen, M. R., 2019. 'Sao Paulo's Strategy for Organic Waste Management.' 11 April 2019. Energy & Waste, Brazil, Latin America, Sao Paulo, Waste Management, Waste-Wise Cities. https://www.urbanet.info/sao-paulo-brazil-organic-waste-management-2/ Accessed: 06.06.2022.

Kaplan., P. Ö., De Carolis, J., Thorneloe., S., 2009. Is It Better to Burn or Bury Waste for Clean Electricity Generation? Environ. Sci. Technol., 43: 1711-1717.

Kaya, K., Ak, E., Aslan, Y., and Oktug, S. F., 2021. 'Waste to Energy Framework: An Intelligent Energy Recycling Management.' Sustainable Computing: Informatics and System. Volume 30, June 2021, 100548.

Kaza, S., Yao, L., Bhada-Tata, P., and Van Woerden, F., 2018. 'What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050.' World Bank Group, Urban Development Series. DOI: 10.1596/978-1-4648-1329-0.

Khan, S., Anjum, R., Raza, S. T., Bazai, N., A., Ihtisham, M., 2022. 'Technologies for Municipal Solid Waste Management: Current Status, Challenges, and Future Perspectives.' Chemosphere, Volume: 288, Part 1, February 2022, 132403.

Khandelwal, H., Thalla A. K., Kumar, S., Kumar, R., 2019. 'Life Cycle Assessment of Municipal Solid Waste Management Options for India.' Bioresource Technology. 288: 121515.

Kranert, M. and Hillebrecht, K., 2000. 'Anaerobic Digestion of organic wastes process parameters and balances in practice.' Internet Conference on Material Flow Analysis of Integrated Biosystems.

Kranert, M., 2017. 'Einführung in die Kreislaufwirtschaft' Planung – Recht – Verfahren, 5. Auflage. ISBN: 978-3-8348-1837-9, ISBN (e-Book): 978-3-8348-2257-4, DOI: 10.1007/978-3-8348-2257-4.

Kulkarni, V. and Ramachandra, T.V., 2009. Environmental Management. Commonwealth of Learning, Canada and Indian Institute of Science, Bangalore, Printed by TERI Press, New Delhi.

Kurbatotova, A. and Abu-Qdais H.A., 2020. 'Using Multi-Criteria Decision Analysis to Select Waste to Energy Technology for a Mega City: The Case of Moscow.' Sustainability, Volume: 12, Issue: 23, 9828. https://doi.org/10.3390/su12239828 Accessed: 06.06.2022.

Laohalidanond, K., Chaiyawonga, P. and Kerdsuwan, S., 2015. 'Municipal Solid Waste Characteristics and Green and Clean Energy Recovery in Asian Megacities.' Energy Procedia, Volume: 79, November 2015, Pages: 391-396.

Lardinois, I., and Furedy, C., 1999. 'Source separation of household waste materials: Analysis of case studies from Pakistan, the Philippines, India, Brazil, Argentina and the Netherlands.' Urban Waste Series 7. Waste.

Larsen, A. W., Merrild, H., Moller, J., Christensen, T. H., 2010. 'Waste Collection Systems for Recyclables: An Environmental and Economic Assessment for the Municipality of Aarhus (Denmark)'. Waste Management, Volume:30, Issue:5, May 2010, Pages: 744-754.

Li, W., and Wang, J., 2021. 'Household Waste Management in Shanghai and Its Implications for the Second-Tier Cities in China.' Journal of Cleaner Production, Volume:321, 25 October 2021, 128980.

Liamsanguan C., Gheewala H.S., 2008. 'LCA: A Decision Support Tool for Environmental Assessment of MSW Management Systems.' Journal of Environmental Management, 87: 132-138.

Limoodehi, F. A., Tayefeh, S.M., Heydari, R., Abdoli, M.A., 2017. Life Cycle Assessment of Municipal Solid Waste Management in Tehran, Environmental Energy and Economic Research, 1(2):207-218.

Lissens, G., Vandevivere, P., De Baere, L., Biey, E. M. and Verstraete, W., 2001. Solid Waste Digestors: Process Performance and Practice for Municipal Solid Waste Digestion. Water Science and Technology. Vol 44 (8): 91-102.

Liu, Y., Chen, S., Chen, A.Y.J and Lou, Z., 2021. 'Variations of GHG emission Patterns from Waste Disposal Processes in Megacity Shanghai from 2005 to 2015.' Journal of Cleaner Production, 10 February 2021, 126338.

Liu, G., Hao, Y., Dong, L., Yang, Z., Zhang, Y. and Ulgiati, S., 2017. 'An Emergy-LCA Analysis of Municipal Solid Waste Management.' Resources, Conservation and Recycling, Volume: 120, May 2017, Pages: 131-143.

López de Munain, D., Castelo, B., Ruggerio, C.A., 2021. 'Social Metabolism and Material Flow Analysis Applied to Waste Management: A study case of Autonomous City of Buenos Aires, Argentina.' Waste Management, Volume: 126, Pages: 843-852.

Löschau, M., 2006. 'Input-Output-Analyse als Methode zur stofflichen Bilanzierung komplexer Entsorgungssysteme.' Dissertation, Fakultät Prozesswissenschaften der Technischen Universität Berlin.

Luk, K., 2021. 'How Strict Waste Management in Japan Alleviated Its Environmental Impact.' Earth.Org, Pollution, 13 September 2021. https://earth.org/japan-waste-management/ Accessed: 04.06.2022

Makinde, O. O. (2012), "Urbanization, housing and environment: Megacities of Africa", International Journal of Development and Sustainability, Vol. 1 No. 3, pp. 976-993.

Mandpe, A., Bhattacharya, A., Paliya, S., Pratap, V., Hussain, A. and Kumar, S., 2022. 'Life Cycle Assessment Approach for Municipal Solid Waste Management System of Delhi City.' Environmental Research, Volume: 212, Part C, September 2022, 113424.

Mata-Alvarez, J., 2003. 'Biomethanization of the Organic Fraction of Municipal Solid Wastes, IWA Publishing Company, Amsterdam, 202-209.

Mattila, T., Helin, T., Antikainen, R., Soimakallio, S., Pingoud, K., Wessman, H., 2011. 'Land use in life cycle assessment.' The Finnish Environment 24,86.

Mavropoulos, A., ISWA, 2010. 'Megacities Sustainable Development and Waste Management in the 21st Century.' ISWA STC Chair, CEO EPEM SA.

Mavropoulos, A., 2010. Waste Management 2030+, Waste Management World, Vol. 11, Issue 2, March 2010. http://www.waste-management-world.com/index/display/article-display/8267238380/articles/waste-management-world/volume-11/issue-2/features/waste-management_2030.html

Mendes, M.R., Aramaki, T., Hanaki, K., 2004. 'Comparison of the Environmental Impact of Incineration and Landfilling in Sao Paulo City as Determined by LCA.' Resource Conservation and Recycling: 41, 47-63.

Mendes, M.R., Aramaki, T., Hanaki, K., 2003. 'Assessment of The Environmental Impact of Management Measures for Biodegradable Fraction of Municipal Solid Waste in Sao Paulo City' Waste Management, 23 (2003), pp. 403-409.

MENR (Republic of Turkey, Ministry of Energy and Natural Resources), 2020. Publication and Reports, National Energy Balance Tables 2020. https://enerji.gov.tr/eigm-raporlari Accessed: 21.06.2023

Metcalf & Eddy, 2003. Tchobanoglous, G., Burton, Franklin, L. Stensel, H. D., 2003. Wastewater Engineering: Treatment and Reuse (4thed.). Boston: McGraw-Hill.

MTS (Metropolitan Transfer Station), 2017. '6 Negative Impacts of Improper Waste Management' https://www.metropolitantransferstation.com.au/blog/negative-effects-of-improper-waste-management. Accessed: 20.08.2020

Miliute, J., Kazimieras Staniskis, J., 2009. Application of Life-Cycle Assessment in Optimisation of Municipal Waste Management Systems: the case of Lithuania, Waste Management Res., 28, 298-308.

Minghua, Z., Xiumin, F., Rovetta, A., Qichang, He.,Vicentini, F., Bingkai, L., Giusti, A., Yi, L., 2009. 'Municipal Solid Waste Management in Pudong New Area, China.' J. Waste Management, 29:1227-1233.

MOEU (Republic of Turkey Ministry of Environment and Urban Planning), 2021. 'Legislation, Regulations, Waste Management Regulations.'
https://cygm.csb.gov.tr/yonetmelikler-i-440

MOEU (Republic of Turkey Ministry of Environment and Urban Planning), 2020. Istanbul Province Zero Waste Management System Plan 2020. Istanbul Governorship, Provincial Directorate of Environment and Urbanization.

MOEU (Republic of Turkey Ministry of Environment and Urban Planning), 2016. Guidelines for the Control of Regular Waste Landfill according to European Union Legislation Books. European Union Network for Implementation and Enforcement of Environmental Law (IMPEL).

MOEU (Republic of Turkey Ministry of Environment and Urban Planning), 2014. Landfill Facilities Field Management and Operation Guide. General Directorate of Environmental Management, Republic of Turkey Ministry of Environmental and Urban Planning.

Moller, J., Christensen T., H., Jansen, Jes la C., 2011. 'Anaerobic Digestion: Mass Balances and Products' Solid Waste Technology & Management, 1: 618-627.

Nayono, S. E., 2010. Anaerobic Digestion of Organic Solid Waste for Energy Production. KIT Scientific Publishing.

Ogundipe, F. O., and Jimoh, O. D., 2015. 'Life Cycle Assessment of Municipal Solid Waste Management in Minna, Niger State, Nigeria. International Journal of Environmental Research, 9(4): 1305-1314, 2015. ISSN: 1735-6865.

Olsson, M., 2015. Industrial Ecology, KTH, Life Cycle Assessment of Waste Management System. The case of Avezzano, Italy, Master of Science Thesis, Stockholm.

Ozeler D., Yetis U., Demirer G.N., 2006. ‘Life Cycle Assessment of Municipal Solid Waste Management Methods: Ankara case study’. Environment International, 32: 405 – 411.

Ozer, B. and Yay, A.S.E., 2021. ‘Comparative Life Cycle Analysis of Municipal Solid Waste Management Systems: Kirklareli/Turkey Case Study.’ Volume: 28, Issue: 45, Page: 63867-63877, Special Issue: SI.

Ozturk, 2010. İ. Ozturk Katı Atık Yönetimi ve AB Uyumlu Uygulamaları ISTAC, Istanbul, Turkey (2010).

Paolini, V., Petracchini, F., Segreto, M., Tomasetti, L., Naja, N., Cecinato, A., 2018. ‘Environmental Impact of Biogas: A Short Review of Current Knowledge.’ Journal of Environmental Science and Health, Part A, 53:10, 899-906.

Peavy, H. S., Rowe, D.R. and Tchobanoglous, G., 1987. Environmental Engineering. New York: McGraw-Hill.

Pre-sustainability (2012). http://www.pre-sustainability.com/simapro-lca-software Accessed: 21.07.2022

Probas, Prozessorientierte Basisdaten für Umweltmanagementsysteme, 2021. Prozesskategorien, Materialien und Produkte, Umwelt Bundesamt https://www.probas.umweltbundesamt.de/php/ Accessed: 26.04.2021.

Rada, E.C., 2016. Solid Waste Management: Policy and Planning for a Sustainable Society.

Rajcoomar, A. and Ramjeawon, T. 2017. ‘Life cycle Assessment of Municipal Solid Waste Management Scenarios on the Small Island of Mauritius’: Waste Management & Research. 35: 313–324.

Ramachandra, 2006. ‘Municipal Solid Waste Management’ Book: Commonwealth of Learning, Canada and Indian Institute of Science, Bangalore, Printed by TERI Press, New Delhi.

Rao, M.S., & Singh, S.P. 2004. Bioenergy Conversion Studies of Organic Fraction of MSW: Kinetic Studies and Gas Yield–Organic Loading Relationships for Process Optimization. Bioresource Technology, 95:173-185.

Recipe, 2016. Huijbregts, M., A., J., Steinmann, Z., J., N., Elshout, P., M., F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., van Zelm R., 2016. 'Recipe 2016: A Harmonised Life Cycle Impact Assessment Method at Midpoint and Endpoint Level.'

Regensburg, 2008. Recycling für den Klimaschutz Ergebnisse der Studie von Fraunhofer UMSICHT und INTERSEROH zur CO_2-Einsparung durch den Einsatz von Sekundärrohstoffen.
https://www.regensburg.de/fm/121/broschuere_recycling_fuer_den_klimaschutz.pdf

Ribas, J. De P., 2015. 'Life Cycle Assessment of Waste Management System. The case of Avezzano, Italy.' Institute of Sustainability, UPC, Master of Science Thesis.

Rigon, M. R., Zortea, R., Moraes, C. A., Modolo, R. C. E., 2019. 'Suggestion of Life Cycle Impact Assessment Methodology: Selection Criteria for Environmental Impact Categories.' Environmental Science. http://dx.doi.org/10.5772/intechopen.83454

Ripaldi, G., 2015. 'Life Cycle Assessment of Waste Management System. The Case of Avezzano, Italy.' Master of Science Thesis, Stockholm. Presented at Industrial Ecology Royal Institute of Technology.

Rousta, K., Bolton, K., Lundin, M., and Dahlen, L., 2015. 'Quantitative assessment of distance to collection point and improved sorting information on source separation of household waste.' Waste Management, Volume: 40, Pages: 22-30), June 2015.

Rushbrook, P., Pugh, M., 1999. 'Solid Waste Landfills in Middle and Lower Income Countries: a Technical Guide to Planning, Design, and Operation.' Pages: 274. World Bank, Washington DC.

Saifullah, A. Z. A. and Islam, Md. T., 2016. ‘Municipal Solid Waste (MSW) Management in Dhaka City, Bangladesh. American Journal of Engineering Research (AJER), e-ISSN: 2320-0847, p-ISSN: 2320-0936, Volume: 5, Issue: 2, pp.: 88-100.

Sala, D., and Bieda, B., 2019. Life Cycle Inventory (LCI) Modelling of Municipal Solid Waste (MSW) Management Systems in Kosodrza, Community of Ostrów, Poland: A Case Study.

Saraiva, A. B., Souza, R. G., Valle, R. A. B., 2017. ‘Comparative Life Cycle Assessment of Alternatives for Waste Management in Rio de Janeiro- Investigating the Influence of an Attributional or Consequential Approach.’ Waste Management, 68: 701-710.

Schenck, R., 2005. Life Cycle Assessment and Sustainability, Third in a Series of Annual Reports on the Green Building Movement, Building Design & Construction, November 2005.

Science Direct, 2022. ‘LCA Publications on Municipal Solid Waste Management (MSWM) in the Megacities.’ ‘Input-Output Analysis Publications on Municipal Solid Waste Management (MSWM) in the Megacities.’ https://www.sciencedirect.com/ Accessed: 30.12.2022.

Shekoohiyan, S., Hadadian, M., Heidari, M., and Hosseinzadeh-Bandbafha, H., 2023. ‘Life Cycle Assessment of Tehran Municipal Solid Waste during the Covid-19 Pandemic and Environmental Impacts Prediction Using Machine Learning, Case Report.’ Case Studies in Chemical and Environmental Engineering. Volume 7, June 2023, 100331.

Sicab, 2020. Sino Italian Capacity Building for Environmental Protection, Thematic Report 15, China Municipal Solid Waste Management Industry, Edited by China-Italy Chamber of Commerce.

Singh, A., Sharma, S., 2002. ‘Composting of a Crop Residue through Treatment with Microorganisms and Subsequent Vermicomposting.’ Bioresource Technology, 85(2): 107-111.

Sonesson, U., Bjorklund, A., Carlsson, M., Dalemo, M., 2000. Environmental and Economic Analysis of Management Systems for Biodegradable Waste. Resource Conservation and Recycling, 28, 29-53.

Springer, C., 2011. Energie- und CO_2-Bilanz von Kompostierungsanlagen – die Basis für einen Effizienzpass. Band 10 der Reihe Manuskripte zur Abfallwirtschaft. Herausgegeben von Bidlingmaier, W., Bauhaus-Universität Weimar und Kranert, M., Universität Stuttgart. Rhombos-Verlag, Berlin 2011.

Swanson, M.B. and Adam C. Socha (Eds.), 1997. Chemical Ranking and Scoring: Guidelines for Relative Assessments of Chemicals. SETAC Press.

Quina, M. J., Bordado, J., and Fereira, R. Q., 2011. 'Air Pollution Control in Municipal Solid Waste Incinerators. Research Centre on Chemical Processes Engineering and Forest Products Department of Chemical Engineering, University of Coimbra. Department of Chemical and Biological Engineering, IBB, Instituto Superior of Tecnico Portugal.

Tabasaran, O., Kranert, M., Öztürk, İ., 2016. 'Katı Atık Yönetimi ve Teknolojileri' ISTAC Co, ISBN: 978-605-63269-8-1, No: 24380.

Tchobanoglous, G., and Kreith, F., 2002. 'Handbook of Solid Waste Management.' McGraw-Hill, Second Edition, 2002.

Tchobanoglous et al., 1993. G. Tchobanoglous, H. Theisen, S.A. Vigil. 'Integrated Solid Waste Management.' Mc Graw-Hill, Singapore (1993).

TeMA, 2016. Pirlone, F., Candia, S., 'MSW from Pollution/Degradation Source to Resource' Journal of Land Use, Mobility and Environment. Tema (2) 2016, 77-93.

Turan, G., Coruh, S., Akdemir, A., Ergon, O., E., 2009. 'Municipal Solid Waste Management Strategies in Turkey Waste Management.' 29: 465–469.

TCA, 2007. Turkish Court of Accounts, 'Waste Management in Türkiye'
http://www.sayistay.gov.tr/english_tca/ Performance/ TCA_Waste_Management_Report.pdf.

TURKSTAT (Turkish Statistical Institute), 2021. 'Population and Amount of Municipal Solid Waste (MSW) Collection in Istanbul and Türkiye by the Years of 2001-2020' 'Municipal Solid Waste (MSW) Data of Istanbul between 2001-2020'. 'Municipal Solid Waste Statistics of Türkiye between 2001-2020.' Municipal Solid Waste Statistics, Environment and Energy Database. https://biruni.tuik.gov.tr/medas/?kn=119&locale=en Accessed: 20.11.2021

TURKSTAT (Turkish Statistical Institute), 2021. Annual Population Growth Rate in Istanbul and Türkiye by Years, 2001-2020. Address Based Population Registration System Results, Population and Demography Database. https://biruni.tuik.gov.tr/medas/?kn=95&locale=en Accessed: 20.11.2021.

Umweltbundesamt, 2010. Frischenschlager, H., Karigl, B., Lampert, C., Pölz, W., Schindler, I., Tesar, M., Wiesenberger, H., Winter, B. Klimarelevanz Ausgewählter Endbericht Recycling-Prozesse in Österreich, Endbericht.

UNEP (United Nations Environment Programme), 2009. Jeftic, L., Sheavly, S. and Adler E. "Marine Litter: A Global Challenge."

UNEP (United Nations Environment Programme), 2005. "Solid Waste Management" Volume 2: Regional Overviews and Information Sources.

UNFCC (United Nations Framework Convention on Climate Change), 1992. FCCC/INFORMAL/84 GE.05-62220 (E) 200705.

UNFCCC, (United Nations Climate Change) 2022. Türkiye 2022, GHG Inventories, Common Reporting Format (CRF) Table, 14 April 2023. https://unfccc.int/documents/627773 Accessed: 21.06.2023.

USEPA (United States Environmental Protection Agency), 2021. Criteria for the Definition of Solid Waste and Solid and Hazardous Waste Exclusions, Definition of Solid Waste. https://www.epa.gov/hw/criteria-definition-solid-waste-and-solid-and-hazardous-waste-exclusions Accessed: 21.07.2021.

USEPA (United States Environmental Protection Agency), 2020. Sustainable Materials Management. 'Energy Recovery from Combustion of MSW.' https://www.epa.gov/smm/energy-recovery-combustion-municipal-solid-waste-msw#EnergyRecovery. Accessed: 02.06.2020.

USEPA (United States Environmental Protection Agency), 2012. 'Landfill Gas Energy' A Guide to Developing and Implementing Greenhouse Gas Reduction Programs, Local Government Climate and Energy Strategy Guides. Energy Efficiency in Local Government Operations.

USEPA (United States Environmental Protection Agency), 2012. 'Understanding Global Warming Potentials.' Greenhouse Gas Emission, Sources of GHG Emissions and Removals. https://www.epa.gov/ghgemissions/understanding-global-warming-potentials#Learn%20why Accessed: 05.08.2020.

USEPA (United States Environmental Protection Agency), 2006. 'Solid Waste Management and Greenhouse Gases A Life Cycle Assessment of Emissions and Sinks.' 3rd Edition.

USEPA (United States Environmental Protection Agency), 2002. 'What Is Integrated Solid Waste Management.' EPA 530-F-02-026a.

USEPA (United States Environmental Protection Agency), 1995. Decision Maker's Guide to Solid Waste Management, Volume II, Chapter 5: Source Reduction. Solid Waste and Emergency Response 5305W. EPA530-R-95-023, August 1995.

USEPA (United States Environmental Protection Agency), 1977. Chapter 8, 'Recycling'. Second Printing, October 1977. An Environmental Protection Publication in the Solid Waste Management Series (SW-601).

Web of Science (WOS), 2022. 'Number of Publications in the Waste, LCA, and Input-Output Analysis Categories. https://www.webofscience.com/wos/woscc/basic-search Accessed: 31.12.2022.

Whiting, A., Azapagic, A., 2014. 'Life Cycle Environmental Impacts of Generating Electricity and Heat from Biogas Produced by Anaerobic Digestion.' Energy, 70:181-193.

WHO (World Health Organization), 2021. 'Ambient (Outdoor) Air Pollution' WHO Newsroom, Air Quality and Health, 22 September 2021.
https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health

WHO (World Health Organization), 2005. 'Particulate Matter, Ozone, Nitrogen Dioxide and Sulphur dioxide' Part 2: Risk assessment of selected pollutants. WHO, Europe, Air Quality Guidelines, Global Update 2005.

Wikimedia Commons, 2017. 'Map of the Districts in Istanbul' https://Istanbul Stadtteile farbkodiert en.voy.jpg - Wikimedia Commons Accessed: 01.02.2021.

Williams, A.S., 2009. 'Life Cycle Analysis: A Step by Step Approach.' Illinois Sustainable Technology Centre, TR-040, December.

World Population Review, 2022. 'World City Populations 2022'
https://worldpopulationreview.com/world-cities Accessed: 03.05.2022

World Population Review, 2023. 'Istanbul Population 2023' 'The Population of Istanbul between 2007 and 2025.' https://worldpopulationreview.com/world-cities/istanbul-population Accessed: 29.06.2023

Worrel, E., Reuter, A., M., 2014. 'Chapter 2- Definitions and Terminology' Handbook of Recycling, State-of-the-art for Practitioners, Analysts and Scientist, Pages: 9-16.

WRAP, 2009. 'Household Food and Drink Waste in the UK, Final Report. Waste & Resources Action Programme.

WRAP, 2008. 'The Food Waste.' Food Waste Report. United Kingdom: Waste & Resources Action Programme.

Yadav, P., Samadder, S.R., 2018. ‘Environmental Impact Assessment of Municipal Solid Waste Management Options Using Life Cycle Assessment: A case study.’ Environmental Science and Pollution Research, 25:838–854.

Yaman, C., 2011. ‘Evaluation of the Current Condition of Packaging Wastes Throughout Istanbul.’ Istanbul Metropolitan Municipality, Istanbul. Scientific Research and Essays Vol. 6 (16), 3378-3388, 19 August 2011. ISSN 1992-2248, 2011 Academic Journals.

Yay, A., Erses, S., 2015. ‘Application of Life Cycle Assessment (LCA) for Municipal Solid Waste Management: A Case Study of Sakarya.’ Journal of Cleaner Production, 94: 284–293.

Yildiz-Geyhan, E., et. al.,2019. Yildiz-Geyhan, E., Yilan G., Altun-Ciftcioglu, G. A., Kadirgan, M. A. N. ‘Environmental and social life cycle sustainability assessment of different packaging waste collection systems.’ Resources, Conservation, and Recycling. 143: 119-132.

Yildiz-Geyhan, E., et. al., 2016. Yildiz-Geyhan, E., Yilan-Ciftci, G., Altun-Ciftcioglu, G. A., Kadirgan, M. A. N. ‘Environmental Analysis of Different Packaging Waste Collection Systems for Istanbul-Turkey Case Study.’ Resources Conservation and Recycling. 107:27-37.

Yilmazi, I ., Yildirim, M., Topkaya, B., 2019. ‘Impacts of Public Participation on the Environmental Impacts of Landfills.’ FEB- Fresenius Environmental Bulletin, Volume: 28, Issue: 2, Page: 608-613, 2019-03-28.

Zhao, R., Sun, L., Zou, X., Fujii, M., Dong, L., Dou, Y., Geng, Y. and Wang, F., 2021. ‘Towards a Zero Waste City - An Analysis from the Perspective of Energy Recovery and Landfill Reduction in Beijing.’ Energy, Volume: 223, 15 May 2021, 120055.

Zhao, W., Voet, E., Zhang, Y., Huppes, G., 2009. ‘Life Cycle Assessment of Municipal Solid Waste Management with regard to Greenhouse Gas Emissions: Case Study of Tianjin, China.’ Science of the Total Environment, 407: 1517-1526.

Zhou, J., Li, L., Wang, Q., Fan, Y., V., Liu, X., Klernes, J., J., Wang, X., Tong, Y., W., and Jiang, P., 2022. ‘Household Waste Management in Singapore and Shanghai: Experiences, Challenges, and Opportunities from the Perspective of Emerging Megacities.’ Waste Management, Volume: 144, 1 May 2022, Pages: 221-232.

CV

1. PERSONAL INFORMATION	
Surname	Capar
Name	Berna
Date of Birth	06.02.1986
Nationality	Republic of Türkiye
Address **Email/Phone**	Akpınar Mah. Kolordu Cad. Aydınlar Apt. No:17 B/1, Elazig, Türkiye bernacapar@gmail.com / (+90 530 165 5611)

2. EDUCATION

Degree	Department	University	City/Country	Date
Ph.D.	Environmental Engineering	Stuttgart University	Stuttgart/Germany	(2014- Today)
Master	Environmental Engineering	Firat University	Elazig/Türkiye	(2010-2011)
Bachelor	Environmental Engineering	Firat University	Elazig/Türkiye	(2004-2009)

3. PUBLICATIONS

Title/Name	Date	Source
Istanbul Metropolitan Municipality, Integrated Waste Management Planning	2011	https://cevre.ibb.istanbul/wp-content/uploads/2022/03/2011-ENTEGRE-ATIK-YONETIMI-PLANI.pdf
Obtaining Drinking Water from Keban Dam Lake with Microfiltration and Reverse Osmosis, Master Thesis	29.06.2011	https://acikbilim.yok.gov.tr/bitstream/handle/20.500.12812/415604/yokAcikBilim_404372.pdf?sequence=-1&isAllowed=y
Municipalities and Waste Management Regulation-I	21.02.2011	Fırat University, Journal of Engineering 23(2), 95-108, ISSN: 1308-9072
Municipalities and Waste Management Regulation-II	21.02.2011	Fırat University, Journal of Engineering 23(2), 109-118, ISSN: 1308-9072

4. WORK/EXPERIENCE

University/Company	Position Held	Duties and Responsibilities	Date
Freelance	Environmental Analyst	Surveying on municipal solid waste management in municipality, researching avoided products, input and output analysis of waste management processes in Germany, studying energy profile and substitution potential in Türkiye, taking LCA training and researching LCA studies on waste management.	August 2016 - Today

Stuttgart University, Institute for Sanitary Engineering, Water Quality Solid Waste Management	Scholarship PhD Student	Studying on municipal solid waste management consepts (Material flow analysis, composting, anaerobic digestion, and incineration)	February 2014 – August 2016
Albayraklar Inc.	Environmental Engineer	Engineer responsible for recycling of packaging waste	August 2011 - November 2011
Proaktif Inc.	Assistance	Project assistance	May 2011 - August 2011

5. COURSE/CERTIFICATES	**Date**
Sima Pro Life Cycle Assessment Training Course/Metsims	December 2018 and June 2017
English Training Course in ST George International London/England	(2012-2013)
TS EN ISO 14001:2004 Environmental Management System	2009
TS EN ISO 9001:2000 Quality Control System Certificate	2009

6. LANGUAGES AND SKILLS
Turkish – Native
English – Advanced
Microsoft Office (Word, Excel, Power Point) – Intermediate

Forschungs- und Entwicklungsinstitut für Industrie- und Siedlungswasserwirtschaft sowie Abfallwirtschaft e.V. (FEI)

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