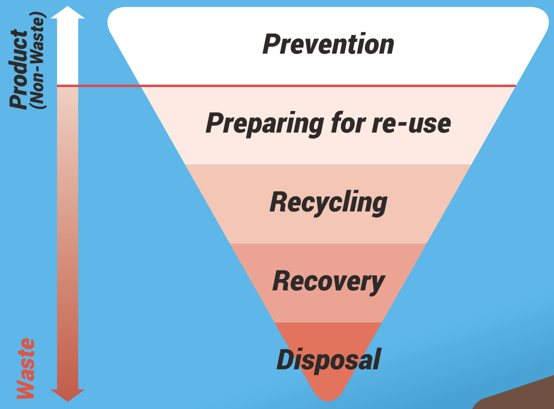
CCET guideline series on intermediate municipal solid waste treatment technologies

Mechanical-Biological Treatment



Social conditions

Public awareness & cooperation of residents

Institutional aspects

Governance capability

Financial aspects

Technological aspects

October 2020

CCET guideline series on intermediate municipal solid waste treatment technologies:
Mechanical-Biological Treatment (MBT)

Authors

Tomonori Ishigaki (National Institute for Environmental Studies, NIES), Chen Liu (Institute for Global Environmental Strategies, IGES)

Project Coordination of CCET Guideline series

Premakumara Jagath Dickella Gamaralalage (IGES), Kazunobu Onogawa (IGES), Yasuhiko Hotta (IGES), Miwa Tatsuno (IGES), Miki Inoue (IGES), Shunichi Honda (United Nations Environment Programme International Environmental Technology Centre, UNEP IETC), and Keith Alverson (UNEP IETC)

Peer Reviewers

Members of the Japan Society of Material Cycles and Waste Management (JSMCWM): Toshihiko Matsuto (Hokkaido University), Mikio Kawasaki (Center for Environmental Science in Saitama), Chart Chiemchaisri (Kasetsart University), Dong-Hoon Lee (University of Seoul), and Toru Nishiyama (IGES)

Acknowledgment

This guideline was prepared by the IGES Centre Collaborating with UNEP on Environmental Technologies (CCET) in cooperation with the UNEP IETC and the Japan Society of Material Cycles and Waste Management (JSMCWM) with financial support from the Government of Japan. The authors and project team would like to thank all involved for their valuable contributions in making this guideline a reality.

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Contents

List of Abbreviations

BOO	Build-Own-Operate
CLO	Compost-like Output
GHGs	Greenhouse Gases
GIZ	German Society for International Cooperation
GTZ	German Technical Cooperation Agency
MBT	Mechanical-Biological Treatment
MSW	Municipal Solid Waste
NIMBY	Not In My Backyard
PFI	Private Finance Initiative
RDF	Refuse Derived Fuel
SDGs	Sustainable Development Goals
SRF	Solid Recovered Fuel

About this Mechanical-Biological Treatment Guideline

Target audience & purpose of this guideline

This guideline focuses on Mechanical-Biological Treatment (MBT) technology for Municipal Solid Waste (MSW), mainly household waste and commercial waste, in urban areas of Asian developing countries.[1] The guideline aims to assist decision-makers and policymakers at the national and city levels and other stakeholders, such as energy plants, as well as manufacturing industries that are seeking sources of alternative fuel, to evaluate the feasibility of introducing MBT technology as an appropriate strategic option for improving waste management. This guideline will:

(1) **provide a holistic understanding** about MBT technology including both **advantages and disadvantages**, as well as information about the **technical and non-technical** aspects of planning a sustainable MBT facility, and

(2) propose **key evaluation criteria** and a **pre-check flow** in the decision-making process to objectively determine and evaluate criteria when considering the potential of introducing MBT technology.

Position of MBT in the waste hierarchy

The introduction of MBT technology should follow the waste hierarchy (Fig. 1). In this scenario, priority is placed on prevention to reduce waste generation, followed by re-use and recycling. Evaluating the waste stream and identifying additional potential for reducing, reusing, and recycling waste are also a critical part of the MSW decision-making process. MBT projects can be categorised as a type of complementary technology for the recovery of energy and for the use of materials in chemical or additional energy processes from remaining non-recyclable MSW. For this reason, measures for MBT technology should not compete with waste reduction, reuse and material recycling measures.

Furthermore, **MBT technology is just one potential element out of many in a functioning MSW system.** It alone cannot solve existing waste problems, and decisions on selecting MBT as an appropriate technology should be made on the basis of an integrated MSW management plan in the respective city or country.

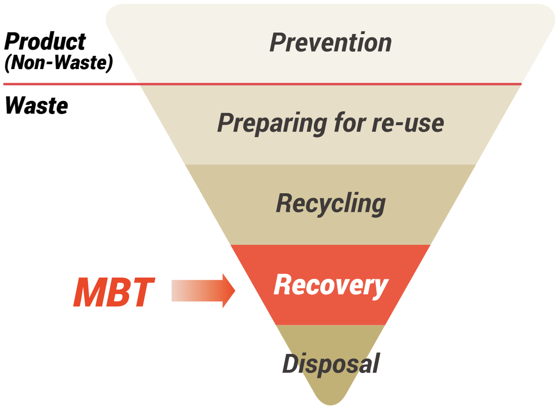

Fig. 1 Waste hierarchy for sustainable waste management (Source: EU Waste Framework Directive[2])

Approach and structure of this guideline

This MBT guideline consists of five main parts: Chapter 1, "Introduction", provides basic information about the concept of MBT technology and its history, advantages and challenges. Chapter 2, "Pre-conditions for Sustainable MBT",

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[1] The terms "developed and developing countries" in the CCET Guidelines are used to define economies as classified by the World Bank in its World Development Indicators report published in 2016. The term "developed countries" refers to high-income countries and regions, while the term "developing countries" encompasses low-income, lower middle income, and upper middle income countries and regions.

[2] EU Waste Framework Directive (Directive 2008/98/EC on waste): https://ec.europa.eu/environment/waste/framework/

describes the key evaluation criteria needed when planning an MBT facility and provides a pre-check framework for sustainable MBT facilities. The key evaluation criteria include technical, as well as non-technical facets, i.e. social conditions, public awareness and cooperation of residents, institutional aspects, governance capability and financial aspects. Chapter 3, "Main Technology", explains the key technologies used in processes at MBT facilities. Chapter 4, "Sustainability and Related Global Issues", covers the SDGs, GHGs, and issues that impact the world, and Chapter 5, "MBT Practices", features actual examples from both developed and developing countries.

Message for the busy reader

Busy readers can look over Chapter 1 to quickly gain a general overview of MBT technology. For readers considering the potential of introducing MBT technology, please use Fig. 5 on page 7 as a guide to check conditions that must be in place at the beginning of the planning stage. Details on the technology involved in MBT can be found in Chapter 3.

1 Introduction

1.1 Definition of mechanical-biological treatment (MBT)

Mechanical-Biological Treatment (MBT) is a pretreatment method used before landfilling to reduce the amount of waste to be disposed.[3] MBT literally means the combination of mechanical crushing and sorting processes and biological treatment (e.g. aerobic and anaerobic decomposition) (Fig. 2). **The advantage of MBT in terms of appropriate waste management is that it can be applied to mixed domestic solid waste without systematic segregation.** An MBT facility can incorporate a number of different processes in a variety of combinations for a wide range of purposes.[4] **An advantage in terms of resources is that MBT can be used to produce Refuse Derived Fuel (RDF) or Solid Recovered Fuel (SRF)[5] and recover recyclable resources, such as metals, through the sorting process.[6]** Biogas can also be recovered through anaerobic digestion. In addition to digestate which is generated from the anaerobic digestion process, a stable organic end product known as Compost-like Output (CLO)[7] is also generated from the aerobic process. **Both digestate and CLO can potentially be used as a source of organic matter on land or to restore landfill caps and can also be repurposed as construction materials, such as backfilling materials or aggregates.** SRF is a fuel produced from non-hazardous waste in compliance with the European standard EN 15359 and also with the developing standard in ISO (TC300). RDF is a collective term referring calorific wastes that is potentially used as fuel without the relevant international official definition. However, there

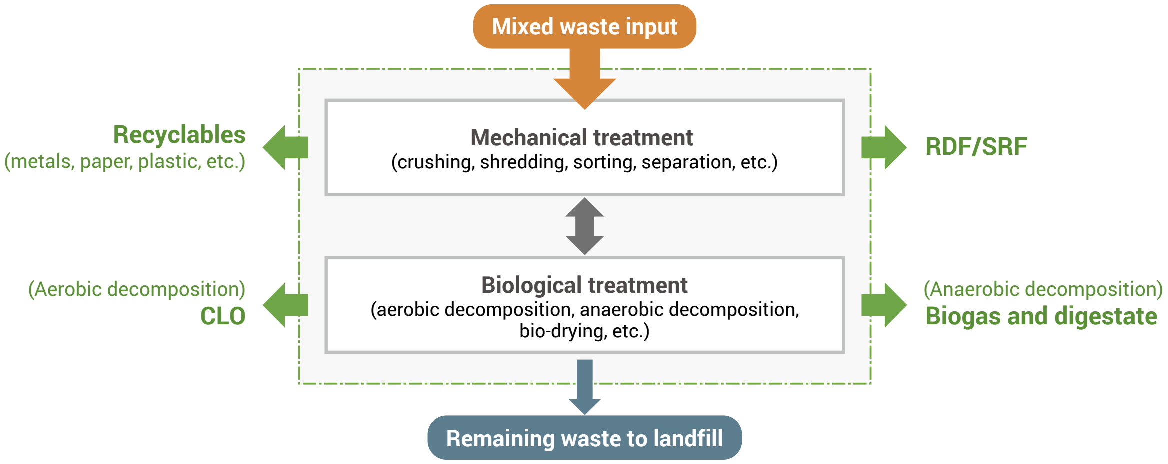

Fig. 2 Typical flow chart of the main processes of MBT

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[3] Barbara Zeschmar-Lahl, Johannes Jager, Ketel Ketelsen (2000) Mechanisch-biologische Abfallbehandlung in Europa, Blackwell Wissenschafts-Verlag, Berlin. ISBN: 978-3826332616

[4] Stephanie, Thiel and Karl Joachim, Thomé-Kozmiensk (2010) Mechanical-Biological Pre-Treatment of Waste – Hope and Reality https://www.iswa.org/uploads/tx_iswaknowledgebase/Thiel.pdf

[5] The category of RDF is defined as the combustible fraction of waste produced by mechanical treatment in the European Waste Catalogue (EWC). To avoid confusion, the abbreviation SRF is used to refer to solid fuels produced by MBT.

[6] Department for Environment, Food & Rural Affairs, UK, (2013) Mechanical Biological Treatment of Municipal Solid Waste

[7] CLO is also sometimes referred to as “stabilised bio-waste” or a soil conditioner; it is not the same as compost derived from source segregated waste or “soil improvers” that have a lower level of contamination and a wider range of end uses.

is a few domestic standrad or rules about RDF, and the definition of SRF in ISO is still under the process as of 2020. Therefore we keep the both description as SRF/RDF in this guideline. In the particular practices, the actual name of the fuel as it is called has been described.

1.2 Historical background and main features of MBT

MBT was originally introduced as a way to pretreat waste before landfilling.[8] Major drivers behind the development of MBT technology include regulatory restrictions on the quality of waste to be landfilled,[9] the search for reasonable pretreatment technology before landfilling, and increased costs of landfill disposal. **The first MBT facilities were developed with the aim of reducing the environmental impact of landfilling residual waste in Europe.**[10] Residual waste is a mixture of waste that is not suited for recycling, is highly diverse in composition and properties,[11] and does not fall under a particular category in source separation schemes. Therefore, the application of MBT for mixed municipal waste is seen as a prospect in developing urban regions in Asia and places the capability of improving recycling rates and extending the service life of landfills directly into the hands of local authorities.

Furthermore, **MBT processes are less energy-intensive than other waste treatment processes and can conserve energy as well as reduce the volume of waste.**[12, 13] In addition, the process of mechanical separation and biological treatment need not rely on advanced technology or high-end machines.[14] The use of localised technology, including **reverse innovation,**[15] is recommended to ensure that MBT processes can be adjusted to local waste properties.[16] The technology to be introduced must be attractive to local governments or other stakeholders that are facing budgetary or financial constraints in enforcing policy measures for improving waste management.

Moreover, MBT systems can form an integral part of a region's waste treatment infrastructure by complementing other waste management technologies[17] to achieve several different aims, including reducing the volume of waste to be landfilled while simultaneously improving the performance of recycling (other than RDF) and recovering biodegradable waste. The **typical objectives of MBT** include:

- **Reducing the amount of waste to be landfilled**
- Diverting non-biodegradable and biodegradable MSW destined for landfills through the mechanical sorting of MSW into **materials for recycling and/or into solid fuels such as RDF or SRF for energy recovery**

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[8] Barbara Zeschmar-Lahl, Johannes Jager, Ketel Ketelsen (2000) Mechanisch-biologische Abfallbehandlung in Europa, Blackwell Wissenschafts-Verlag, Berlin. ISBN: 978-3826332616

[9] The Council of the European Union (1999) Council Directive 1999/31/EC on the Landfill of Waste, Official Journal of the European Communities, L182,16/07/1999, pp1-19

[10] Joern Heerenklage, Rainer Stegmann (1995) Overview of mechanical–biological pretreatment of residual MSW, Proceedings Sardinia 1995, fifth international landfill symposium, pp 913–925

[11] Eunomia Research & Consulting (2002) Ecomomic Analysis of options for managing biodegradable municipal waste, Final Report to the European Commission https://ec.europa.eu/environment/waste/compost/pdf/econanalysis_finalreport.pdf

[12] Eunomia Research & Consulting (2002) Ecomomic Analysis of options for managing biodegradable municipal waste, Final Report to the European Commission https://ec.europa.eu/environment/waste/compost/pdf/econanalysis_finalreport.pdf

[13] Kardono, Agung Riyadi, Widiatmini Sih Winanθ, Wahyu Purwanta, Annex1-3 Technology factsheets waste sector, Mechanical-biological treatment (MBT), Indonesia Technology Needs Assessment for Climate Change Mitigation 2012

[14] Klaus Fricke, Heike Santen, Rainer Wallmann (2005) Comparison of selected aerobic and anaerobic procedures for MSW treatment. Waste Management 25, 799–810

[15] Reverse innovation, also referred to as "trickle-up innovation", is a technology or practice first developed or used in the developing world before spreading to the industrialised world.

[16] Maria Chiara Di Lonardo, Francesco Lombardi, Renato Gavasci (2012) Characterization of MBT plants input and outputs: a review: Reviews in Environmental Science and Bio/Technology, 11, 4, 353-363

[17] Matthias Kuehle-Weidemeier (2015) Waste to Energy and Re-sources, More Sustainability by Mechanical Biological Treatment (MBT) http://giecdn.blob.core.windows.net/fileuploads/file/kuehle-weidemeier_mbt1.pdf

- Diverting biodegradable MSW sent to landfills by **reducing the dry mass of biodegradable municipal waste or reducing the biodegradability of municipal waste prior to landfill**
- **Stabilising waste into CLO** for use on land
- **Converting waste into a combustible biogas** for energy recovery
- **Drying materials to produce a high-calorific, organically-rich fraction** for use as RDF/SRF

The main advantages, disadvantages and requirements of MBT from different perspectives are summarised in Table 1.

Table 1 Main advantages, disadvantages and requirements of MBT

	Advantage	Disadvantage	Requirement*
Waste	1. Reduced volume of waste destined for landfills	1. Poor quality of dry recyclables separated out during the MBT process	1. Management of debris such as rejected solid fuels or CLO
Technology	1. High feasibility of use in combination with existing technology 2. Advanced technology or high-end machines not required 3. Suitable for moist MSW with anaerobic digestion or bio-drying before separation	1. Unsuitable for bulky waste, liquid waste and night soil	1. Essential to adapt drying and separation processes for waste in Asia with high moisture levels, as well as for waste that is organic 2. Need for initial waste sorting process to remove foreign objects and improve efficiency
Economic implications	1. Intensive, low-energy method 2. Savings in fuel costs for users of RDF/SRF 3. Potential use of CLO as soil conditioners or back filling materials 3. Can be adapted to markets for recyclables, RDF/SRF, CLO and biogas	1. RDF/SRF consumption depends on fuel price and industrial situation 2. Essential to consider the limited pool of industrial consumers of RDF/SRF in Asian markets, risk of overstock of rejected RDF/SRF or increase in volume of waste for disposal 3. Fewer benefits in using CLO	1. Crucial to secure multiple sales channels for RDF/SRF 2. Profits expected from sales of valuable metals and CLO for income rather than treatment costs. In contrast, the cost for disposal of debris should be taken into account even though it has potential for use as CLO.
Public health	1. Less infectious and toxic than dumpsites	1. Waste not effectively sanitised compared to thermal treatment or composting	1. Important to regulate and screen feedstock for non-hazardous waste
Environment	1. Less environmental pollution from landfills 2. Efficient for resource and energy recovery and conserving natural resources such as soils, metals and fuels	1. Projections for noise, vibration, dust and waste volume 2. Potential emissions of atmospheric pollutants by RDF/SRF consumers	1. Important to regulate and screen feedstock for non-hazardous waste
GHG emissions	1. Lower GHG emissions in the overall process of waste management	1. Increased emissions of nitrous compounds from landfills as a result of low C/N debris	1. Life cycle assessments recommended

* Does not include common issues in other waste management facilities that need to be considered, such as plant/facility siting, traffic, air emissions, dust/odours, bio-aerosols, flies, noise, litter, waste resources, design principles, public concerns, etc.

(Source: author)

1.3 Opportunities and challenges for cities in developing Asian countries

Several attempts have been made to transfer MBT technology to developing countries in Asia[18] and South America.[19] However, these efforts have mostly failed to adapt the technology to local conditions and results have been limited. **In recent years, especially in Southeast Asia where urban development has been remarkable, the focus of attention has been redirected to the introduction of MBT as a technology to cope with the increase in waste volume as well as the promotion of 3R (reduce, reuse and recycle) policies.**[20, 21]

MBT is recommended for:

(1) **Cities that are becoming more urbanised and need to develop integrated waste management, but do not have a stable financial base or external/internal support, and/or have poor source separation practices**

(2) **Cities with an industrial base that can use RDF/SRF,** such as the existence of a cement industry, remaining capacity at a lignite power plant or WtE plant, or heat demand at a paper manufacturer in the wood industry

MBT may be attractive to (Fig. 3):

(1) A local authority that wants to **maximise landfill space** and is continuing to manage waste by direct disposal, and/or is **looking for a cost-effective pretreatment method before landfilling**

(2) A waste management company or local authority that wants to **leverage economic incentives from waste management and recycling**

(3) An industry that is aiming to **save on fuel costs, or to expand the utilisation of recyclable materials**

(4) A central government that is aiming to **expand the utilisation of renewable energy**

Local Authority

- that wants to enhance regional resource efficiency
- that is looking for cost-effective pretreatment methods before landfilling
- that must maximise landfill capacity

Waste to Resource Industry

- that wants to expand the economic incentives from waste management and recycling

Central Government

- that wants to expand the use of renewable energy
- that is shifting to a circular economy

Industrial User

- that wants to save fuel costs, or to expand the possible uses of recyclable materials

Fig. 3 Users that can benefit from MBT

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[18] Tomonori Ishigaki, Ssatoru Ochiai, Masato Yamada, Dong-Hung Lee, Jae-Ram Park, Komsilp Wangyao (2016) Applicability of MBT in Middle Scale and Small Scale Municipality in Asia, The 9th Inter-continental Landfill Research Symposium, pp.100-101.

[19] Alberto Bezama, Pablo Aguayo, Odorico Konrad, Rodrigo Navia, Karl E Lorber (2007) Investigations on mechanical biological treatment of waste in South America: towards more sustainable MSW management strategies. Waste Management, 27, 228–237

[20] Nemanja Stanisavljevic, Paul H Brunner (2014) Combination of material flow analysis and substance flow analysis: A powerful approach for decision support in waste management, Waste Management & Research, 32, 8, 733-744

[21] International Solid Waste Association Task Force (2014) Globalization and Waste Management https://www.iswa.org/index.php?eID=tx_iswaknowledgebase_download&documentUid=3818

However, the characteristics of MSW in developing countries in Asia differ from that in developed countries due to differences in consumption levels and lifestyles. This means that the reasoning behind the demand for MBT technology also varies. For European Countries those were forced to introduce the pretreatment of MSW in accordance with EU directive,[22] the main role of MBT facilities is to stabilise organic waste and recover valuable recyclable materials. For developing countries, where at least 50% of MSW contains organic waste,[23] the amount of recyclables present in waste is much lower as these materials are separated out by the informal recycling sector.[24] In this context, **the demand for MBT facilities in Asia is primarily for the treatment of organic waste and utilisation of byproducts (such as RDF, SRF, biogas and CLO), while the separation of recyclables has a limited overall effect.** Although a variety of treatment and mechanical separation options are available,[25] the use of this output as byproducts must be optimised in order to identify outlets for the variety of materials and fuels derived from the MBT process.

The key to sustainable MBT is securing a market for RDF/SRF. Because of the limited number of industrial furnaces in developing countries compared to developed countries, potential consumers must be found in wide areas (inter-city or inter-province) for a broad range of applications. Competition with other RDF/SRF manufacturers and other alternative fuels can find these manufacturers struggling to meet high-quality requirements from consumers, for example, setting a calorific value of 5,000 kcal/kg,[26, 27] which is close to that of coal. In some cases, efforts are made to slightly improve sorting efficiency to raise the quality of RDF/SRF to match market needs. Meanwhile, there are cases where waste only undergoes biological treatment with little sorting to reduce the volume of landfilled waste.

Waste such as food waste or inedible parts of fruits or vegetables in Southeast Asia has high levels of moisture and organic matter.[28] The introduction of such waste into the MBT process may result in poor crushing and sorting efficiency. Therefore, the moisture content of waste must be lowered before the start of the MBT process. Solar drying is possible under some conditions,[29] but other problems exist, including odours, scattering of garbage and vulnerabilities to sudden precipitation. Endogenous heat during the biological process must be applied prior to the use of heat, such as a bio-drying process in which organic matter is decomposed and dried by generated heat using a biological reaction.[30] Waste heat is sometimes used for drying RDF/SRF, but this type of valuable, high-quality energy is better used as high-density energy flux.

Above all, the choice of introducing MBT technology depends on the size of the city, industrial concentration, and the feasibility of improving the transportation environment, which should be reviewed in line with the growth of the city and the region as a whole.

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[22] The Council of the European Union (1999) Council Directive 1999/31/EC on the Landfill of Waste, Official Journal of the European Communities, L182,16/07/1999, pp1-19

[23] World Bank (2018) What a Waste Global Database, https://datacatalog.worldbank.org/dataset/what-waste-global-database

[24] Agamuthu Pariatamby (2017) Chapter 3 Waste Management, *In* Asia Waste Management Outlook, UN Environment Programme

[25] Stephanie, Thiel and Karl Joachim, Thomé-Kozmiensk (2010) Mechanical-Biological Pre-Treatment of Waste – Hope and Reality https://www.iswa.org/uploads/tx_iswaknowledgebase/Thiel.pdf

[26] Jidapa Nithikul, Obulisamy Parthiba Karthikeyan, Chettiyappan Visvanathan (2011) Reject management from a mechanical biological treatment plant in Bangkok, Thailand, Resources, Conservation & Recycling, 55, 417–422

[27] Satoru Ochiai, Tomonori Ishigaki, Komsilp Wangyao, Masato Yamada (2014) Adaptability of Mechanical Biological Treatment in Tropical Asia, A Case Study in Thailand, 25th Annual Conference of Japan Society of Material Cycles and Waste Management, pp.625-626

[28] Ashok V Shekdar (2009) Sustainable solid waste management: An integrated approach for Asian countries, Waste Management, 29, 1438-1448

[29] André Guimarães Ferreira, Lindomar Matias Gonçalves, Cristiana Brasil Maia (2014) Solar drying of a solid waste from steel wire industry. Applied Thermal Engineering, 73, 104–110.

[30] Costas Velis, Philip John Longhurst, Gillian H. Drew, Richard Smith, Simon James Trent Pollard (2009) Biodrying for mechanical-biological treatment of wastes: a review of process science and engineering, Bioresource Technology 100, 11, 2747–61.

2 Pre-conditions for Sustainable MBT (RDF/SRF)

Before making a political decision to select MBT as an appropriate waste treatment technology for the overall waste management system, it is necessary to have a comprehensive understanding and evaluate the situation from various perspectives in order to ensure that MBT is implemented in a sustainable manner. There have been numerous examples where "proven" technologies in developed countries have failed in developing countries because sufficient attention was not paid to "soft" strategic aspects, namely, political, institutional, social, financial, economic and technical elements.[31, 32] Although each MBT facility requires a site-specific approach, it is possible to identify a few key generic factors.

In this guideline, **key evaluation criteria can be verified from six perspectives–social conditions, public awareness and cooperation of residents, institutional aspects, governance capability, financial aspects and technical aspects (Fig. 4)**. Following the six perspectives together with relative key evaluation criteria for each, **a modified pre-check flow (Fig. 5) can be used as a guide at the beginning of the planning stage.** The key evaluation criteria and pre-check flow are presented to assist decision-makers and policymakers in taking a closer look at whether local conditions are suitable for MBT technology and developing a transparent assessment of what technology best fits with these conditions. This does not, however, replace the need for a professional assessment on feasibility when planning a MBT project. Only after confirming its probability for success should a project move on to the next step, which is a more detailed feasibility study and implementation plan for introducing appropriate technology before the actual construction of a MBT facility, as shown in Fig. 4.

Key evaluation criteria are divided into three groups: **(1) mandatory key criteria (in pink), (2) strongly advisable key criteria (in yellow), and (3) advisable key criteria (in green).** Arrows should be followed to proceed to the next step in cases where evaluation criteria are met. If criteria have not been met, the following actions are recommended:

(1) **in cases where mandatory key criteria are not met, MBT is not yet suitable.** It is strongly recommended that the evaluation be suspended or that the situation be re-evaluated after improvements are made;

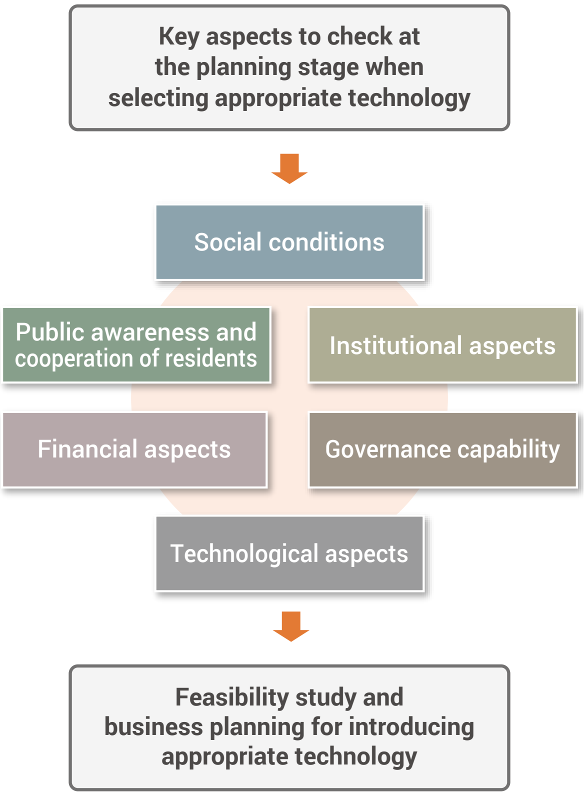

Fig. 4 Key aspects to check at the planning stage when selecting appropriate technology

(Source: author)

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[31] International Solid Waste Association Task Force (2014) Globalization and Waste Management https://www.iswa.org/index.php?eID=tx_iswaknowledgebase_download&documentUid=3818

[32] Kai Münnich, Gunnar Ziehmann, Klaus Fricke (2002) Biological pre-treatment of municipal solid waste in low income countries, Proceedings of International Symposium on Environmental Pollution Control and Waste Management, p.293-303.

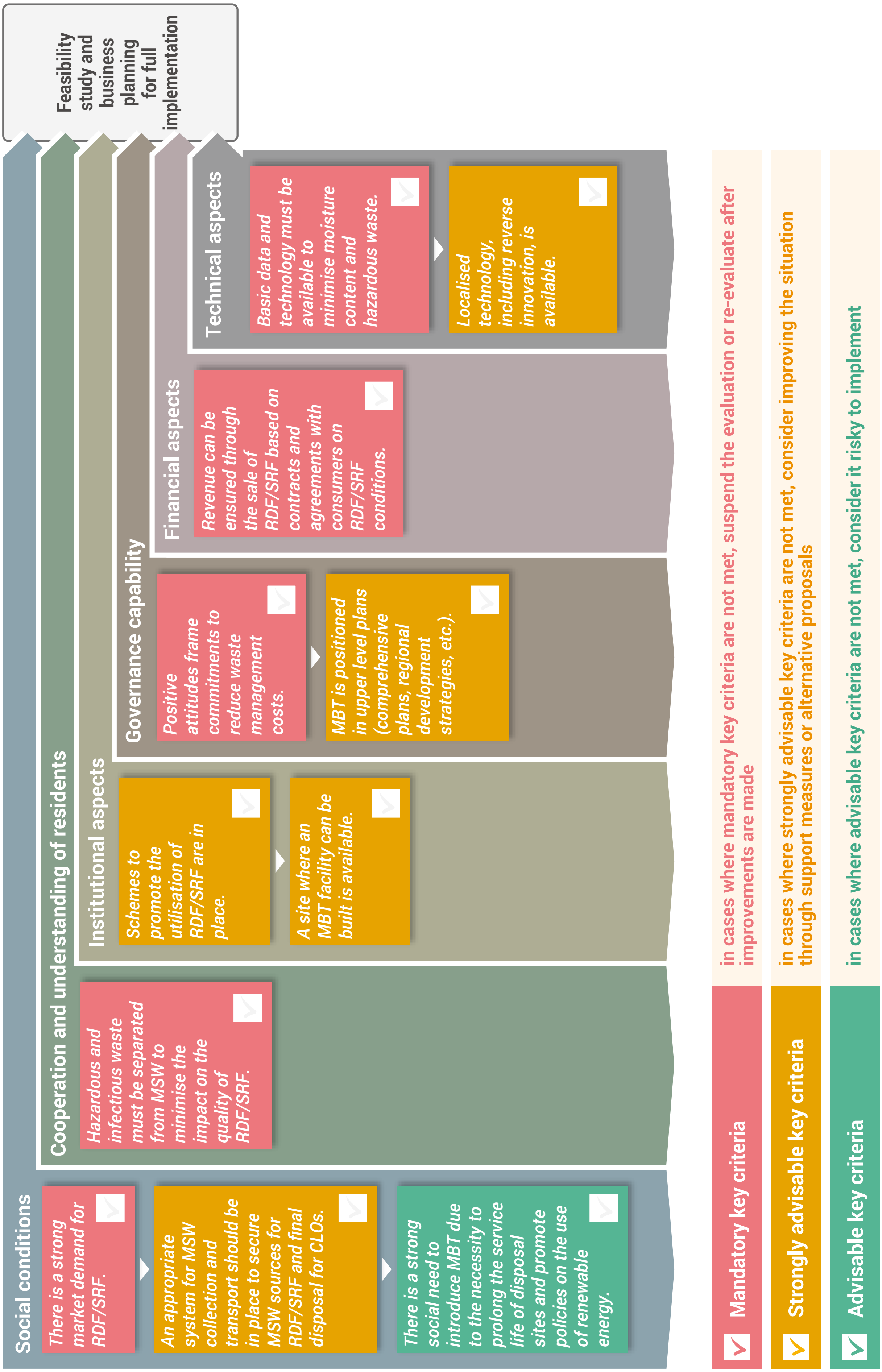

Fig. 5 Pre-check flow to be conducted at the beginning of the planning stage when developing MBT projects

(Source: author)

(2) in cases where strongly advisable key criteria are not met, **support measures should be introduced, or alternative proposals considered;**

(3) in cases where advisable key criteria are not met, **caution should be exercised as MBT can be risky to implement.**

In addition, considering that the main purpose of MBT in developing countries in Asia is the separation of a fraction of RDF/SRF and that the "CCET guideline series on intermediate municipal solid waste treatment technologies: Composting" and "CCET guideline series on intermediate municipal solid waste treatment technologies: Waste-to-Energy Incineration" have been designed as part of the same series, this guideline mainly focuses on RDF/SRF, and the related issues of composting and anaerobic digestion technology are not addressed here in detail.

2.1 Social conditions

2.1.1 Secure users of RDF/SRF

☑ **Mandatory key criteria**

There is a strong market demand for RDF/SRF.

The local region should possess a strong industrial background to ensure the continuous and stable utilisation of RDF/SRF. **Sustainable operation can only be achieved with industrial furnaces, waste incinerators, or RDF/SRF power plants.** For example, cement kilns that are located within a profitable distance would be potential users of RDF/SRF.[33, 34] Lignite power plants are also some of the biggest users of RDF/SRF in Europe and could have similar potential in Asia.[35] Pulp and paper manufacturers also require alternative fuel for their boilers.

Contracts between RDF/SRF providers (MBT owner/operator) and users are mainly based on the quality of RDF/SRF and the market price of fossil fuels. On top of that, a key factor for the successful distribution of RDF/SRF is a relationship of mutual trust with local consumers. Industrial RDF/SRF users generally require a stable supply of fuel in terms of quality and quantity. If there are no issues with waste collection and transportation systems, RDF/SRF production will be stable in terms of the amount produced. RDF/SRF is not strong in terms of cost competitiveness,[36] and therefore, should be consumed as close as possible to the local region. RDF/SRF must prove that it can offer consumers the level of quality they require. The application of regional or international standards may be needed to ensure the quality of RDF/SRF.

In order to increase the marketability of RDF/

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[33] ECOFYS (2016) Market opportunities for use of alternative fuels in cement plants across the EU http://www.titan.rs/public/uploaded_files/ecofysreport_wastetoenergy_2016-07-08.pdf

[34] Costas A Velis, Philip John Longhurst, Gillian H. Drew, Richard D Smith, Simon James Trent Pollard (2010) Production and quality assurance of solid recovered fuels using mechanical-biological treatment (MBT) of waste: a comprehensive assessment. Critical Reviews in Environmental Science and Technology 40, 12, 979–1105

[35] Thomas Glorius (2009) SRF in a CHP-plant in Germany ERFO Conference om Solid Recovered Fuels (SRF) – A sustainable option for Spain

[36] Jan Theulen (2013) Standardization as a help to facilitate SRF acceptance and use, Experience of the European Cement Industry http://www.eu-projects.de/Portals/11/08_Theulen_ERFO.pdf

SRF, legislation promoting the use of recycled materials, e.g. green procurement, can be applied to increase the use of RDF/SRF, although it can have an adverse effect on a large segment of businesses and industries in the region. A Feed-in Tariff on renewable energy use is also an effective measure to promote the use of RDF/SRF which contains renewable fractions.

2.1.2 Secure feedstock for RDF/SRF

✓ Strongly advisable key criteria

An appropriate system for MSW collection and transport should be in place to secure MSW sources for RDF/SRF and final disposal for CLOs.

In general, **MBT can be applied to any population size because its treatment capacity can be flexibly expanded by changing the machinery used.** In terms of the efficiency of mass treatment, MBT is recommended for small- to middle-scale municipalities (e.g. population of less than 100,000). However, it is essential to secure a certain quantity and quality of MSW. Future changes in composition as a result of the implementation of policies such as reducing plastic, for example, should be taken into consideration because it can affect the stable production and quality of RDF/SRF. For example, existing formal and informal schemes for recycling paper and plastic affect the quality of RDF/SRF.

2.1.3 Social needs

✓ Advisable key criteria

There is a strong social need to introduce MBT due to the necessity to prolong the service life of disposal sites and promote policies on the use of renewable energy.

It is necessary to identify the needs of the society for introducing MBT, such as requirements to prolong the service life of disposal sites, which include both illegal waste disposal areas and landfills, as well as to promote policies on the use of renewable energy and so on. It is essential to come to an agreement on constructing MBT facilities, as well as other waste management facilities. If all segments of society are willing to expand landfill capacity, they will proactively support the construction of MBT facilities. Alternatively, if there are any objections against WtE incineration, for example, there may be passive or no support for the implementation of MBT.

2.2 Public awareness and cooperation of residents

☑ **Mandatory key criteria**

Hazardous and infectious waste must be separated from MSW to minimise the impact on the quality of RDF/SRF.

To avoid the loss of RDF/SRF value through contamination with hazardous compounds, it is essential that people cooperate to remove waste containing hazardous substances. Toxic chemicals as well as infectious waste must be carefully separated from domestic waste that will be sent to MBT facilities.[37, 38]

2.3 Institutional aspects

☑ **Strongly advisable key criteria**

Schemes to promote the utilisation of RDF/SRF are in place.

Commonly accepted and universal quality standards for RDF/SRF should be put in place through agreements based on common testing methods. Standards on quality will lower the barrier for potential RDF/SRF users and will expand the market. Although there may be quality standards in Europe[39], Japan[40] or the United States[41] that may be of reference, it is recommended that **country-based or regional-based standards be established based on local conditions.** Global standards are currently being developed by the International Organization for Standardization (ISO) and will be published at a later date.[42]

☑ **Strongly advisable key criteria**

A site where an MBT facility can be built is available.

Securing a construction site is a fundamental part of satisfying requirements and achieving the goals of MBT plans. Sites are also subject to various laws and restrictions, such as urban planning and building standards, so it is important to advance plans from a comprehensive perspective.

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[37] Kardono, Agung Riyadi, Widiatmini Sih Winanθ, Wahyu Purwanta (2012) Annex1-3 Technology factsheets waste sector, Mechanical-biological treatment (MBT), *In* Indonesia Technology Needs Assessment for Climate Change Mitigation 2012

[38] Vera Susanne Rotter, Thomas Kost, Joerg Winkler, Bernd Bilitewski (2004) Material flow analysis of RDF-production processes, Waste Management, 24, 1005–1021

[39] CEN, EN15359 (2011) Solid Recovered Fuels—Specifications and Classes. Brussels, CEN

[40] JIS Z 7311 (2010) Refuse derived paper and plastics densified fuel.

[41] ASTM E856-83(2004) Standard Definitions of Terms and Abbreviations Relating to Physical and Chemical Characteristics of Refuse Derived Fuel

[42] Rieko Kubota Development of SRF standard in ISO TC300, Knowledge sharing seminar on RDF production, utilization, standardization seminar

2.4 Governance capability

Mandatory key criteria

Positive attitudes frame commitments to reduce waste management costs.

The introduction of MBT projects is influenced by political needs in local governments. The head of the local government must have a positive and open attitude towards the construction and operation of MBT facilities. The roles of related departments in local governments must be clarified initially, with officers in charge appointed by the head of the local government.

Meanwhile, MBT is often regarded as a traditional type of technology for treating mixed MSW in a practical and reasonable way in cases where the level of technology and economic scale are less mature in terms of incineration or other types of technology used for mass treatment.[43] **MBT is recommended for municipalities that cannot afford to introduce high-cost treatment technology, such as incineration.** Therefore, it is important to confirm the cost-effectiveness of implementing MBT to reduce municipal budgets for waste management.[44, 45] MBT should always be assessed against its impacts, such as reductions in the amount of waste sent to the landfill, energy produced, revenue, and other benefits. These relevant targets and indicators shall be clearly shown and shared in advance before the project is implemented, irrespective of whether the facility is operated by the public or private sector. Local governments should maintain the right to advise private contractors (i.e. special purpose companies, SPC), in order to maximise the effectiveness of the project as demonstrated by indicators, as well as the monetary value of the project.

Strongly advisable key criteria

MBT is positioned in upper level plans (comprehensive plans, regional development strategies, etc.).

MBT should be formally/legally recognised in upper level plans such as comprehensive plans, regional development strategies, and other relevant plans. Specific master plans or policy initiatives will be also effective in realising its implementation. When MBT is positioned in such plans, facility design, construction and operation, as well as actions to educate the public, will move forward smoothly.

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[43] International Solid Waste Association Task Force (2014) Globalization and Waste Management https://www.iswa.org/index.php?eID=tx_iswaknowledgebase_download&documentUid=3818

[44] Kardono, Agung Riyadi, Widiatmini Sih Winanti, Wahyu Purwanta (2012) Annex1-3 Technology factsheets waste sector, Mechanical-biological treatment (MBT), *In* Indonesia Technology Needs Assessment for Climate Change Mitigation 2012

[45] Satoru Ochiai, Tomonori Ishigaki, Masato Yamada (2015) Comparison of Mechanical Biological Treatment Operations Based on Cost and Benefit in Asia, 2nd 3R International Scientific Conference on Material Cycles and Waste Management, pp.210-213

2.5 Financial aspects

☑ **Mandatory key criteria**

Revenue can be ensured through the sale of RDF/SRF based on contracts and agreements with consumers on RDF/SRF conditions.

MBT involves a wide range of costs depending on the complexity of the technology, especially when considering the biological process to be adopted and the degree of mechanisation and automation to be employed. MBT systems are also particularly sensitive to markets for recycled materials, RDF/SRF and CLO that are produced by different processes because tradability and marketability are strongly affected by fossil fuel conditions.[46] Partnerships between MBT operators and potential users of outputs should be established at the earliest opportunity and care should be taken to ensure facilities can deliver materials of sufficient quality for the required market (DEFRA, 2013). In particular, unsold RDF/SRF will become a burden for MBT operators if they must be stored at the facility, an indication that it must be disposed of in landfill sites. Securing RDF/SRF consumers is essential not only for the successful operation of MBT facilities, but also for sustainable waste management in the region. SRF can be used in a wide variety of industries for heat and power generation, such as industrial furnaces and boilers, as well as in municipal facilities, such as SRF power plants and district heating and cooling services.[47] There should be no expectations that the sale of RDF/SRF will result in strong profits because sales can be highly unstable depending on contract and market conditions. In this way, these **profits should not be considered as a major form of revenue in budget estimations, although it may account for some income.**

In addition, as with other MSW technology, the costs of MBT projects (capital and operating costs) must be secured. **Subsidies or loans must be prepared from the local government's own budget to cover the costs for operation** (e.g. maintenance of equipment, fuel, electricity, tipping fees, etc.), **and reliable investors must be involved.** Tipping fees are normally taken into consideration when the disposal of debris is outsourced. MBT processes and landfill management are not always handled by the same sections.

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[46] ECOFYS (2016) Market opportunities for use of alternative fuels in cement plants across the EU http://www.titan.rs/public/uploaded_files/ecofysreport_wastetoenergy_2016-07-08.pdf

[47] Eleni Iacovidou, John Hahladakis, Innes Deans, Costas Velis, Phil Purnell (2018) Technical properties of biomass and solid recovered fuel (SRF) co-fired with coal: Impact on multi-dimensional resource recovery value, Waste Management, 73, 535-545

2.6 Technological aspects

✓ Mandatory key criteria

Basic data and technology must be available to minimise moisture content and hazardous waste.

MBT is suitable for mixed domestic waste and residual waste that does not fall under other categories in source separation schemes. Even though MBT is suitable for treating mixed domestic waste, the high moisture content is a technical barrier to proper treatment in terms of efficient mechanical separation.[48] The bio-drying process is efficient in removing moisture, ensuring that the waste can be sorted, which increases the quality of RDF/SRF. The removal of food waste in advance will also increase the efficiency of the separation process and result in the production of high-quality RDF/SRF.[49] Since domestic waste in the tropical climate of Asia has a higher moisture content than that in European countries,[50] it is essential to dry MSW before it is physically separated, although the input of energy for heating should be prevented as much as possible in order to reduce additional operating costs. Industrial waste, which is mainly composed of paper, plastics and wood, can also be used for MBT, although these wastes are more suitable as recyclables. Hazardous waste should not be mixed in with waste, as hazardous compounds, including toxic, infectious, or explosive matter in materials, may affect the quality of RDF/SRF. Bulky waste, liquid waste and night soil are also not suitable for MBT. Specific waste to be avoided for MBT shall be decided by local laws and regulations and through contracts with RDF/SRF consumers.

✓ Strongly advisable key criteria

Localised technology, including reverse innovation, is available.

As mentioned above, the process for mechanical separation and biological treatment does not need to rely on advanced technology or high-end machines. **The use of localised technology, including reverse innovation, is recommended to ensure that MBT can be adapted to local waste properties.**

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[48] Kardono, Agung Riyadi, Widiatmini Sih Winanθ, Wahyu Purwanta (2012) Annex1-3 Technology factsheets waste sector, Mechanical-biological treatment (MBT), *In* Indonesia Technology Needs Assessment for Climate Change Mitigation 2012

[49] Maria Chiara Di Lonardo, Francesco Lombardi, Renato Gavasci (2012) Characterization of MBT plants input and outputs: a review: Reviews in Environmental Science and Bio/Technology, 11, 4, 353-363

[50] Ashok V Shekdar (2009) Sustainable solid waste management: An integrated approach for Asian countries, Waste Management, 29, 1438-1448

3 Main Technology

3.1 General technical requirements

MBT is a comprehensive system that combines two processes: **a mechanical process (waste preparation and separation) and biological process (aerobic or anaerobic waste decomposition, and bio-drying).** The mechanical and biological processes can be arranged in either order, with mechanical treatment preceding biological treatment or vice versa (Fig. 6).

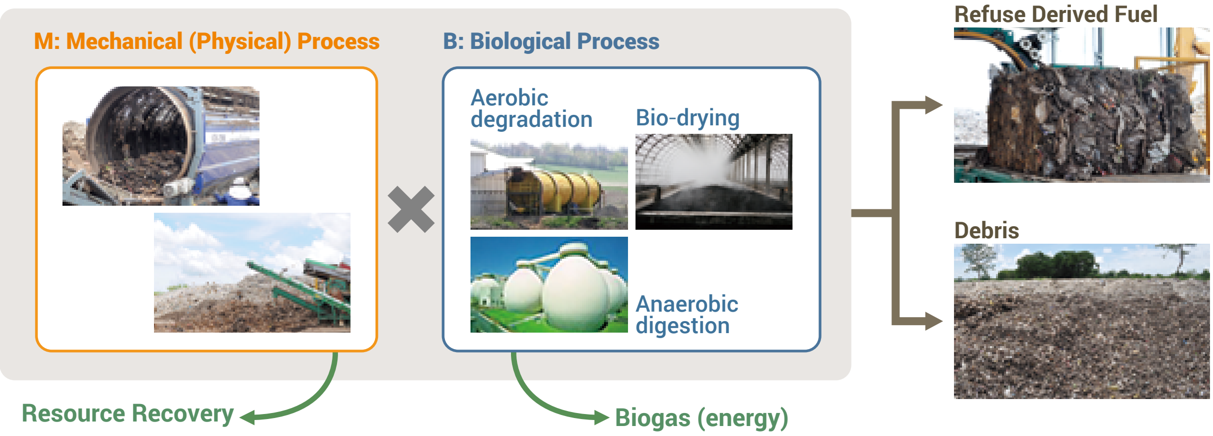

Fig. 6 Brief outline of MBT system

3.1.1 Waste preparation

MSW must be prepared before biological treatment or materials are sorted, such as removal, shredding, and crushing. Initial waste preparation may take the form of the simple removal of unsuitable objects, such as mattresses, carpets or other bulky wastes, which may cause problems with processing equipment downstream. Additional mechanical waste preparation techniques may be used to prepare the materials for subsequent separation stages. The objective of these techniques may be to split open refuse bags, thereby liberating the materials inside, to shred and homogenise the waste into smaller particle sizes suitable for a variety of separation processes, or to perform subsequent biological treatment depending on the MBT process employed (DEFRA, 2013). A summary of the different techniques used for waste preparation is provided in Table 2.

Table 2 Waste preparation techniques

Technique	Principle function	Key concerns
Hammer mill	Material significantly reduced in size by swinging steel hammers.	Wear on hammers. Pulverising and 'loss' of glass/aggregates. Excludes pressurised containers.
Shredder	Rotation of knives or hooks at slow speeds with high torque. The shearing action tears or cuts most materials.	Potential for large, rigid objects to physically damage the shredder. Excludes pressurised containers.
Bag splitter	Relatively gentle shredder used to split plastic bags whilst leaving the majority of the waste intact.	No reduction in size of waste. Potential for large, rigid objects to damage the splitter.
Manual separation	Separation of plastics, contaminants and oversized materials from waste by hand.	Ethics of roles, health and safety issues.

3.1.2 Waste separation

Separation technologies exploit the varying properties of different materials in the waste. This includes the size and shape of different objects, density, weight, magnetism, and electrical properties (DEFRA, 2007). **Sorting the waste allows the MBT process to separate different materials that are suitable for different end uses and sequential processes, including material recycling, biological treatment, energy recovery through the production of RDF/SRF, and landfill.** A variety of different techniques can be employed, and most MBT facilities use a series of several different techniques in combination to achieve specific end use requirements for different materials. A summary of the different options for waste separation is shown in Table 3.

Table 3 Waste separation techniques

Separation technique	Separation property	Target material	Key concerns
Trommels and screens	Size	Oversized paper, plastic Small organics, glass, fine fractions	Air containment and cleaning
Magnetic separation	Magnetic properties	Ferrous metals	Proven technique
Eddy current separation	Electrical conductivity	Non-ferrous metals	Proven technique
Air classification	Weight	Light plastics, paper Heavy stones, glass	Air cleaning
Ballistic separation	Density and elasticity	Light plastics, paper Heavy stones, glass	Rates of throughput
Optical separation	Diffraction	Specific plastic polymers	Rates of throughput
Vibrating screen	Size and density	Plastic film, paper, sheets, sand and stones	Mesh size, accelerated vibration, rates of throughput

3.1.3 Biological treatment

The biological processes used in MBT include **aerobic decomposition, aerobic bio-drying, and anaerobic digestion.** There are a variety of different biological treatment techniques used in MBT facilities (DEFRA, 2013). The aerobic decomposition process is similar to composting though the product quality is not always comparable. This process aims to maximise the decomposition of degradable organic matter in domestic waste. Therefore, aeration rates or frequency of turning is optimised for microbes in the decomposition process.

The addition of moisture or growth of microbial cells will lower the quality of RDF/SRF, although the quality of CLO may improve. In contrast, aerobic bio-drying aims to maximise the evaporation of moisture in domestic waste.[51] Since the main heat source is also biological decomposition, aeration and turning processes are also performed. However, microbial growth must be controlled because it acts as a moisture sink and impedes drying. These bacterial cells, also known as heat scavengers, consume heat and inhibit efficient evaporation.

Anaerobic digestion is a familiar process used in

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[51] Costas Velis, Philip John Longhurst, Gillian H. Drew, Richard Smith, Simon James Trent Pollard (2009) Biodrying for mechanical-biological treatment of wastes: a review of process science and engineering, Bioresource Technology 100, 11, 2747–61.

the management of livestock manure or septage in Asian countries.[52, 53] The isolated use of anaerobic digestion often fails due to the low rate of production of biogas because of a lack of organic matter for anaerobic microbes. **It is recommended that the anaerobic digestion process in MBT be linked with other organic sources to produce a feasible amount of biogas.** Table 4 below outlines the key categories of biological treatment. In some processes, all the residual MSW is biologically treated to produce stabilised output for disposal to landfills where no sorting is required.

Table 4 Biological treatment options

Options	Key concerns
1	Aerobic decomposition: Open piles or in-vessel reactors, which are generally used for sludge, night soil, bio-waste or segregated organic-rich fractions
2	Aerobic bio-drying: Optimised for reducing moisture in waste
3	Anaerobic digestion: Generally used for sludge, night soil, bio-waste, or segregated organic-rich fractions

3.2 Typical MBT processes in developing Asian countries

The mechanical process in MBT is not a single process but a sequence of processes that use several technologies. **In developing countries in Asia, the main purpose of the mechanical process is to separate fractions for RDF/SRF.** Appropriate technology must be selected according to the physical properties of waste to maximise the quality of RDF/SRF. This, however, does not require advanced technology to be used, and a combination of locally available separation techniques can be examined before implementation.

The anaerobic degradation process is almost the same as anaerobic digestion (see the “CCET guideline series on intermediate municipal solid waste treatment technologies: Anaerobic Digestion”). However, anaerobic digestion is unsuitable for unit processes in mixed domestic waste in Asia due to the low putrescible fraction in the dry base. **To enable the successful implementation of anaerobic digestion, continuous and stable biogas emissions are required.** If stakeholders are resolute in their willingness to use biogas and there is a social and industrial basis to do so, the mechanical separation process must be performed prior to anaerobic digestion (Fig. 7-a). Otherwise, since the residue from this process contains a certain amount of organics and moisture, it will be technically and practically difficult for waste to be treated with MBT in terms of RDF/SRF production, and additional processes may be required for post-treatment. Another option for the anaerobic digestion process is to utilise external anaerobic digestion facilities for treating suitable waste, or to be designed for treating suitable waste such as organic sludge, agricultural waste, green waste and others (Fig. 7-b).

The aerobic degradation process requires the introduction of air for microbes; however, a high-aeration rate, such as is used in the composting

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[52] International Atomic Energy Agency (2008) Guidelines for Sustainable Manure Management in Asian Livestock Production Systems https://www-pub.iaea.org/MTCD/Publications/PDF/TE_1582_web.pdf

[53] Tiffany Joan Sotelo, Hiroyasu Satoh, Takashi Mino (2019) Assessing Wastewater Management in the Developing Countries of Southeast Asia: Underlining Flexibility in Appropriateness, Journal of Water and Environment Technology, 17, 5, 287–301

process, is not appropriate for MBT, although the bio-drying process is favourable for energy, material recovery and cost efficiency in MBT for mixed waste in tropical countries. The basic technology used in bio-drying is similar to that used in composting, although bio-drying is not optimised for biodegradation.[54] Bio-drying maximises the evaporation of moisture in waste by using the heat generated through biodegradation. The biggest advantage of bio-drying is its ability to help increase separation efficiency before the mechanical process (Fig. 7-c). Open-air pile, windrow or other locally developed technology in the open air are more suitable than in-vessel reactors from the perspective of cost and technological feasibility, although practices in developed countries may demonstrate a level of effectiveness with in-vessel bioprocesses or bioreactors in waste decomposition.[55, 56]

In addition, the efficiency of reducing the volume of waste and producing RDF/SRF is determined by the order of the mechanical and biological processes. In considering the high moisture content of domestic waste in developing countries in Asia, biological treatment is often performed prior to mechanical separation in order to increase separation efficiency. It is for this reason that the biological process in this region focuses more on drying than decomposition or digestion.

Also, final waste that is not suitable for RDF/SRF due to size, contamination or moisture is generally disposed of in final landfills. While it is regarded as CLO, its utilisation in the environment as backfilling material should be carefully controlled to avoid becoming a source of pollution.[57, 58] RDF/SRF is recommended for use in closed areas, such as for cover materials in waste landfills.

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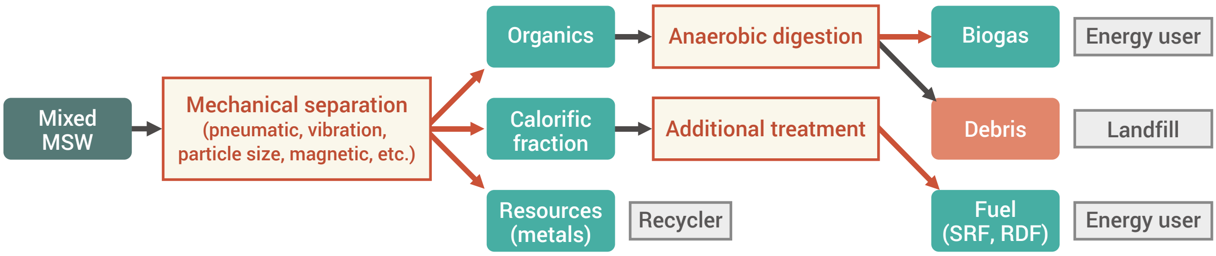
[54] Costas Velis, Philip John Longhurst, Gillian H. Drew, Richard Smith, Simon James Trent Pollard (2009) Biodrying for mechanical-biological treatment of wastes: a review of process science and engineering, Bioresource Technology 100, 11, 2747–61.

[55] Costas Velis, Philip John Longhurst, Gillian H. Drew, Richard Smith, Simon James Trent Pollard (2009) Biodrying for mechanical-biological treatment of wastes: a review of process science and engineering, Bioresource Technology 100, 11, 2747–61.

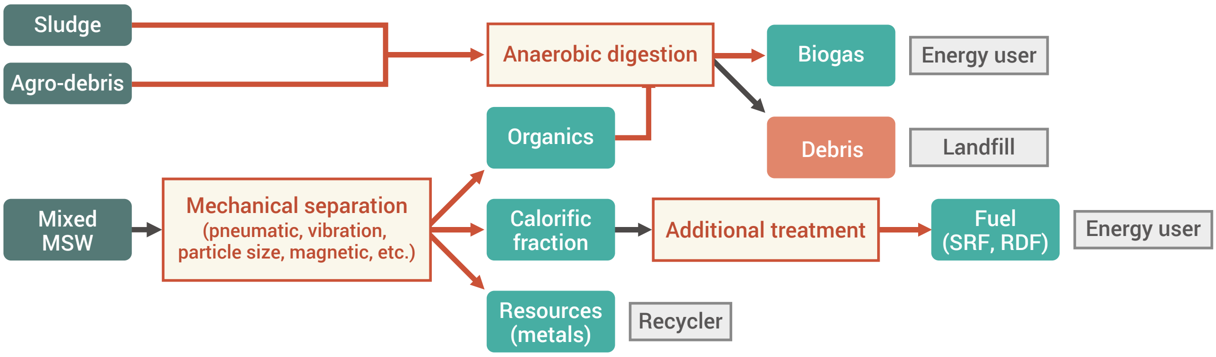
[56] Kardono, Agung Riyadi, Widiatmini Sih Winanθ, Wahyu Purwanta (2012) Annex1-3 Technology factsheets waste sector, Mechanical-biological treatment (MBT), *In* Indonesia Technology Needs Assessment for Climate Change Mitigation 2012

[57] Maria Chiara Di Lonardo, Francesco Lombardi, Renato Gavasci (2012) Characterization of MBT plants input and outputs: a review: Reviews in Environmental Science and Bio/Technology, 11, 4, 353-363

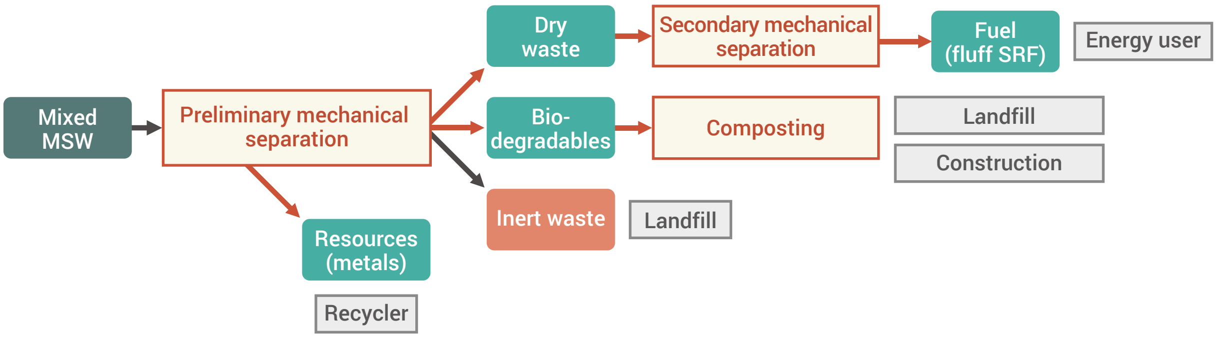
[58] Agency for Environmental Protection and Technical Services (2006) Effetti dell’impiego di frazione organica stabilizzata in attivita` di ripristino ambientale Report 65/2006



(a) Anaerobic digestion in the MBT system



(b) Mechanically separated organic fraction treated in an external anaerobic digestion process



(c) Bio-drying process adopted in the MBT system

Fig. 7 Typical flow of materials and technology in MBT

4 Sustainability and Related Global Issues

4.1 GHGs and climate change

MBT can reduce the direct emission of Greenhouse Gases (GHG) through waste treatment in comparison with direct disposal, thermal treatment, or biological treatment (generally, emissions from MBT < emissions from disposal site < emissions from incineration). Indirect GHG emissions can also be reduced by (i) maintaining low consumption levels for energy, fuel and chemicals in energy-driven operations, (ii) substituting emissions from the utilisation of fossil fuels with SRF depending on biogenic carbon content, and (iii) reducing methane emissions from disposal sites by reducing the degradable carbon in waste. In addition, the reduction of degradable organics in waste sent to landfills also reduces landfill-related environmental pollution. MBT debris has a low C/N ratio, and its effect on the behaviour of substance conversion in landfills is not known.

4.2 SDGs

The main contributions of MBT to the SDGs is shown in Table 5.

Table 5 Main contributions of MBT to the SDGs

	Contribution to SDGs
Overall	“Achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimise their adverse impacts on human health and the environment” (12.4) “Substantially reduce waste generation through prevention, reduction, recycling and reuse” (12.5)
Production of RDF/SRF as fuel for power and heat generation	“Increase substantially the share of renewable energy in the global energy mix” (7.2)
Recovery of recyclable materials (metals)	“Improve progressively through 2030 global resource efficiency” (8.4)
Utilisation of CLO for construction	“Achieve the sustainable management and efficient use of natural resources” (12.2)
Reduction of GHG emissions in the waste management system	“Improve human/institutional capacity on climate change mitigation” (13.3)
Reduction of landfill-related environmental pollution	“Reduce the adverse environmental impact of cities, including by paying special attention to waste management” (11.6) “Significantly reduce the release of waste to air, water and soil in order to minimise their adverse impacts on human health/environment” (12.4)

5 MBT Practices

5.1 Phitsanulok, Thailand

Brief introduction and key points

An MBT facility was introduced in Phitsanulok (Fig. 8) to treat mixed MSW. It featured a unique system that worked in combination with a national flagship cement company to produce RDF that was mostly transported to a cement kiln owned by the company. The MBT facility is now closed but had helped reduce the volume of waste sent to landfills in this region and reduced the municipality's budget for waste management.

Historical background

MBT was implemented to overcome the issue of a lack of waste disposal capacity in the region. The MBT system (FABER-AMBRA) was initially implemented with technical support from the German Technical Cooperation Agency (GTZ) in 2000. After construction, the facility was operated by the local subsidiary of a cement company under a contract with the municipality. From the beginning of the project, solid fuels produced from this process were planned for use in cement kilns, indicating a strong co-dependency on the company's own situation, which also ultimately became the reason for its closure.

Mixed domestic waste collected from the urban district in Phitsanulok City and the surrounding municipalities was treated at the facility, which received 100 tonnes/day on average. The collected MSW comprised organic waste (food and plants, 40.3%), plastics (41.7%), inorganics (8.2%) and other types of waste (9.8%) in a dry-based evaluation. The average initial moisture content was 52.9%.

The facility was operated efficiently for more than 15 years in terms of waste treatment. In contrast, the cement company was not always satisfied with the situation because of the low quality of RDF due to contamination from high moisture organics and waste containing chloride, which was not directly loaded into the kiln but was refined on the treatment line at the cement company. This additional process generated unusable residue up to 20-30% of RDF, which was rejected and returned to the municipality. A secondary reason for the company's dissatisfaction with the situation was transportation. The distance from the MBT facility to the cement kiln was about 350 km. This distance combined with the limited route (highway) posed a problem in relation to accidents and disasters. In the end, the cement company terminated its contract with the municipality and shifted to another RDF produced in a facility that could transport it faster.

Implementation and enablers

(a) Social conditions

Since the MBT facility was operated by the subsidiary of the cement company, the cement kiln was secured as a stable RDF customer. RDF was provided free to the cement company under a concession agreement for waste treatment. When the lower heating value of RDF exceeded 21 MJ/kg, the cement company received a refund of about THB 100 (approximately USD 3.2)/kg. Even though there had been limited success in marketing RDF because of its low quality, there was no need to seek a new user under this scheme. For the cement company, it was essential to procure alternative fuels, an issue that was solved by this concession agreement.

With a population of about 70,000 in an area of 18 km^2, Phitsanulok is not such a large city. However, there were objections from residents near the landfills because such sites had always been located in provincial areas. They felt that this was unfair and complained, which strongly motivated the local government to maximise the capacity of an existing landfill in this area. The MBT facility was located at an existing landfill site, allowing it to be more favourably accepted by the surrounding residents as a solution to landfill-related problems. The utilisation of RDF was also consistent with the national goal of promoting renewable energy with a target to increase energy production from waste in 2035 by 10 times the figure recorded in 2014.

(b) Public awareness and cooperation of residents

Residents were well-informed about the importance and necessity of avoiding contaminating domestic waste with hazardous waste in order to maintain RDF quality. Residents in the urban area of Phitsanulok City cooperated by separating hazardous waste as this type of waste has not been found in successive composition analyses.

(c) Institutional aspects

The cement company demonstrated internal quality requirements for RDF of more than 0.3 of bulk density, a lower heating value of more than 18.8 MJ/kg, and less than 0.8% of chlorine content. The cement company itself was able to adjust the final quality of alternative fuel with the addition of other types of waste, such as tires or plastics separated at source.

Since this MBT facility was constructed on remaining land at the existing landfill site, there were no barriers to securing a site for constructing and operating the facility. The MBT process was initially introduced as a positive way to address social objections to the construction and operation of the landfill site.

(d) Governance capability

Costs are always higher when a waste management system with MBT is compared with a simple disposal scheme. German Society for International Cooperation (GIZ), the funding agency for the introduction of the MBT facility, initially estimated that additional capital and operation costs would be EUR 5.1/Mg of waste and EUR 5.7/Mg of waste, respectively. A cost-benefit analysis revealed that the advantages (value) of RDF would be two to seven times higher than the operation cost for RDF production. On the other hand, this estimation does not include the capital cost of MBT or the cost of residue treatment. The value of RDF must be efficiently assessed in terms of the return on investment in order to generate a profit.

Phitsanulok City has a “zero landfill policy” in MSW management, which was also developed through technical support from GIZ. This policy was based on the concept of the 3Rs (Reduce, Reuse, and Recycle) that was also set out in a national agenda by the Government of Thailand, and covers public participation and technological implementation to reduce the amount of waste sent to the landfill. Public participation was promoted through a programme on community-based solid waste management, which greatly enhanced public awareness and cooperation in public waste management services. MBT was a key technology used to cover the reduction of waste to be landfilled.

(e) Financial aspects

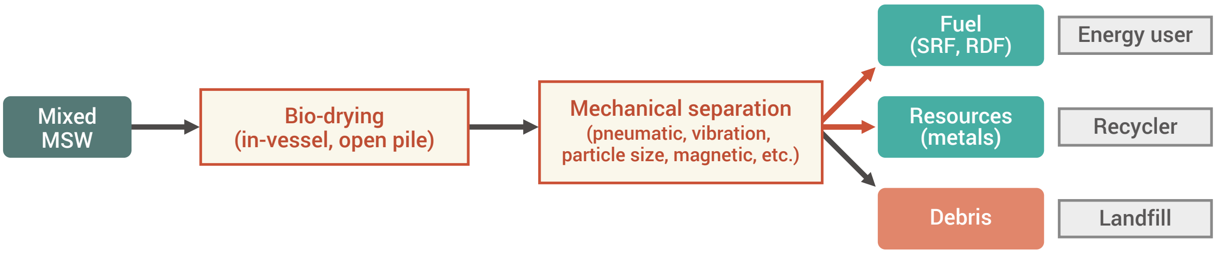
Even though parts of the facility were constructed with support from an international development scheme with GIZ, most of the facility was installed and updated by a local cement company. Therefore, the operating scheme was considered to be close to a Private Finance Initiative (PFI) scheme. In this scheme, the procurement of a budget, design and construction of the facility were initially implemented by the public sector with international funds, after which the responsibility for operation was transferred to the private sector.

(f) Technological aspects

The entire MBT process in this facility consisted of several phases. At first, MSW was de-bagged and homogenised with a rotating drum. Homogenised MSW was piled on a pallet plate and maintained for several months (MBT windrow) for the purpose of bio-drying. The waste was configured in a shape with a dimension of 50 m (w) x 170 m (l) x 4.0 m (h). Apparent density was estimated to be 625 kg/m^3. During that period, passive aeration was also naturally promoted to stabilise the waste. Convective air flow was performed due to the temperature difference between the waste layer and the ambient air. A ventilation pipe was installed at the centre of the waste pile to increase gas exchange. The penetration of air into the waste layer promoted the increased activity of the aerobic microbes responsible for the decomposition of solid waste. Generally, this process of bio-drying took around nine to eleven months.

Next, the stabilised waste was transferred to a separation facility to produce solid fuel. The separation processes consisted of a trommel, disc screen, pneumatic separation, and magnetic separation. Components of the waste which were not suitable for use in solid fuel were partly utilised as a cover layer for the bio-drying pile but were mostly disposed as debris at the landfill site.

The production of SRF was estimated to be 30% of the initial amount of fresh waste, but 20-30% of SRF was rejected by the cement kilns and returned for landfilling. Even taking this into consideration, the amount of waste only comprised 15% of the initial amount of fresh waste. Operations were sometimes temporarily suspended due to customer-specific conditions, culminating in the cancellation of the contract with the cement company.



Bio-drying area at MBT facility in Phitsanulok

RDF produced in Phitsanulok

Fig. 8 MBT practices in Phitsanulok, Thailand

5.2 Nashik, India

Brief introduction and key points

The MBT system in Nashik (Fig. 9) is used to treat mixed municipal waste. It was not an organised system at first, but a mechanical process that had been introduced to produce RDF in order to treat the large amount of unsellable waste fractions (also known as compost rejects). The produced compost is used for agriculture, and RDF is used in local industries.

Historical background

With more than a million people, Nashik is a well-known holy city for Hindus in the state of Maharashtra. Waste generation is among the lowest in India at 0.22 kg/capita/day due to ineffective collection and the active (but informal) use of organics as fertiliser in the local horticulture industry. Although the composting facility for municipally collected waste had been in operation before the introduction of MBT, the efficiency of compost production was low due to the preliminary recovery of organics. The amount of produced compost was estimated at 3-5% of input waste, and compost rejects accounted for 60%. Therefore, a mechanical separation process to produce RDF was introduced to reduce the volume of compost rejects which would instead be disposed of at the landfill site.

The MBT facility was fully updated in 2016 under a 30-year concession contract with a private company. Mixed domestic waste treated in this sequential system amounts to 500 tonnes/day. RDF is traded in fluff form although it had been previously pelletised, and is then used in industries and power plants in the region. In India, coal power plants are the second largest source of generated power. Adding to public awareness on environmental problems caused by the use of coal, changing regulations, coal shortages, soaring coal prices and frequent plant shutdowns have also increased the need for alternative sources of solid fuels. Therefore, RDF is expected to be a potential solution for stabilising the coal crisis in the country.

Implementation and enablers

(a) Social conditions

RDF produced in this facility is currently utilised in regional industries, such as cement kilns and power generation plants, but its trading situation is unstable. Even though MBT operations and RDF production fluctuate, it is essential to secure a stable customer base to ensure sustainable operations. Potential customers for RDF include the manufacturing industry and power generation plants.

Nashik is an important city involved in an infrastructure development project known as the Golden Triangle Project, which also involves the cities of Mumbai and Pune. This project has promoted the growth, expansion and development of the social, economic and industrial situation in Nashik. In addition, improvements to the transportation network has increased accessibility to the Navi Mumbai Special Economic Zone that is permitted to generate power in captive power plants. The industrial utilisation of RDF in this area points to the potential of a large market. Recent worldwide objections against coal power plants, however, could act as a force to advance the use of RDF in the country. The Nashik thermal power station located 10 km away from central Nashik is also a coal power plant with a capacity of 630 MW. This is one candidate that may become a regional customer for RDF in the near future.

Forecasts on population growth, industrial development, and enhancement of the proper collection of municipal waste is compelling Nashik City to institute an integrated solid waste management system. In order to maximise landfill capacity, the MBT process is expected to play an important role together with the effective introduction of the formal source separation of hazardous and organic wastes.

(b) Public awareness and cooperation of residents

Although the Maharashtra state has documented the rules and guidelines for the source separation of hazardous MSW such as old medications, paints, fluorescent tubes, spray cans, fertilisers and pesticide containers, batteries, and shoe polish, contamination still often occurs. The handling of contaminated RDF is a secondary problem requiring further dissemination of information and improved public awareness to address this situation. Both RDF and compost consumers are anxious about the potential for contaminating MSW. Since residents have also realised the importance of avoiding contaminating waste to promote the utilisation of compost and alternative fuel, their cooperation will be essential in an efficient scheme involving the collection of separated hazardous waste by the municipality.

(c) Institutional aspects

The national government (Central Public Health and Environmental Engineering Organisation, Ministry of Housing and Urban Affairs) has released a guideline for the use of RDF in various industries in India, including quality standards for its utilisation in Waste-to-Energy plants and the cement industry. RDF is categorised into three grades by its intended use, size, contents of ash, moisture, chlorine, sulfur, and lower heating value. The highest grade RDF, which is used for direct co-processing in cement kilns, requires less than 10% of ash, 10% of moisture and 0.5% of chlorine, and a lower heating value that is higher than 18.8

MJ/kg, for example. This guideline does not have any legal force nor a formal certification system, but customers may have a certain reliance on RDF.

The MBT facility is located in a waste management complex which includes a sanitary landfill and incinerators used for purposes other than for MBT. It is located close to the city border in an area that has not been developed for residences or businesses, even though it is only 10 km away from the city centre. Although there have been no strong objections from residents about safety to date, this facility is located behind the ancient religious ruins of Pandav Leni Caves, and care should be taken to protect the regional environment in terms of odour, noise, fumes, waste projections and sanitation to prevent complaints from the tourism industry.

(d) Governance capability

Forecasts on population growth in Nashik provide strong motivation for the development of cost-efficient waste management. Problems with earlier systems stemmed from the low tradability of low-quality compost and RDF because of the lack of a stable customer base. A new concession scheme with a private company will increase the value of both CLO as compost and RDF and is expected to improve the cost-benefit balance.

Upgrading the aging composting plant to an MBT facility has been outlined in Nashik's 2011 solid waste management plan. This is also mentioned in governmental rules on solid waste management in 2016 and is regarded as an important process for reducing landfilled waste, increasing CLO quality, and producing alternative fuel nationwide.

(e) Financial aspects

A thirty-year design, finance, build, operate and transfer (DFBOT) contract was awarded to a local Pune-based joint venture of an Indian and French conglomerate. This public-private partnership was launched to introduce an integrated waste management model that included improvements to waste collection, dissemination of information and practices on source separation, improved landfill management and repairing and upgrading machinery in the existing MBT facility. In terms of the RDF price, a governmental committee suggested that the price be expressed as a fixed price according to the heating value for usage in cement industries. The recommended price was INR 0.4/1,000 kcal (approximately USD 1.34/MJ). For example, when the RDF meets quality standards for the highest-grade category (18.8 MJ/kg), the price will be INR 1,800/tonne of RDF (approximately USD 25.2/tonne).

(f) Technological aspects

The preliminary mechanical separation process was mainly divided into three categories: dry waste (< 100 mm of particles), biodegradable waste (20-100 mm), and inert waste (> 20 mm). Dry waste, including wood, paper, textiles, and jute, was processed to produce RDF. Waste was put through the process of drying, size reduction, sieving, and homogenisation, and then finally shredded to produce fluff. This fluff RDF was then further processed to produce pellets or briquettes as per customer requirements. The RDF was utilised in the surrounding industries and power plants as boiler fuel. After the facility was updated, several problems were discovered with regard to operation, resulting in a capacity to produce about 20 tonnes/day of RDF. However, the city plans to increase capacity to 80-100 tonnes/day due to strong demand from customers.

Biodegradable waste and fine fractions from the preliminary mechanical separation process, comprised of 40% domestic waste, were treated with windrow composting. Similar to other composting plants in India, the produced compost yield was very low (10%) and generated a portion of rejected fractions because of contamination from plastics or other unsuitable materials for compost. There were also frequent stoppages due to mechanical problems. The calorific value of rejected fractions was about 12,000 kJ/kg, and therefore, it was expected to be utilised as material to produce RDF. Unless used, this rejected compost needed to be disposed into landfills together with inert waste. In this case, the effects on waste reduction were not as high as expected in terms of maximising landfill capacity.

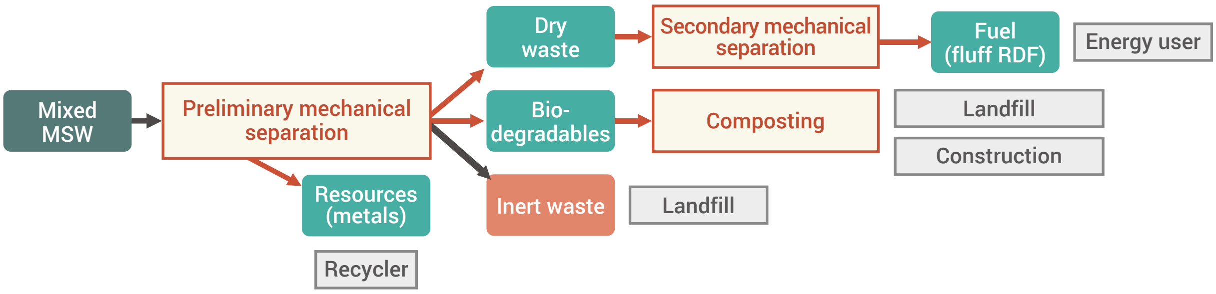


Fig. 9 MBT practices in Nashik, India

5.3 Rayong, Thailand

Brief introduction and key points

The MBT facility in Rayong, Thailand (Fig. 10) is part of an integrated waste management system from Rayong's Waste-to-Energy centre under a contract between Rayong Province and a public company producing and supplying power. About 500 tonnes/day of mixed domestic waste was delivered to the mechanical separation process first, with 30% converted to SRF with a calorific value around 14,000-17,000 kJ/kg. Previously, SRF was sent to cement kilns, but has recently been utilised in a private SRF power plant. Small size waste accounted for 45% of the input waste sent to the composting production line. Although these two segments of the mechanical and biological processes were operated by different companies, an MBT system is considered to include a sequential process for waste treatment. The recyclable fraction from the mechanical separation process is about 5% of input waste and is sold to private recyclers. Any remaining debris is sent to the landfill which is also a part of the province's integrated waste management system.

Historical background

Rayong Province is an industrial, agricultural and tourism hub in eastern Thailand. Population, economic and industrial development has led to a significant increase in the amount of MSW (over 1,000 tonnes/day). Previously, each local authority in Rayong managed MSW in their own areas. In 2007, about 68 local authorities signed an agreement to install an integrated solid waste management facility called "Rayong Waste-to-Energy", developed along the policy of the Ministry of Interior and managed by the Rayong Province Administrative Organization (Rayong PAO). This project focuses on reducing waste at source. Transfer stations are provided for local authorities that are located far from this integrated WtE facility. However, the various local authorities in Rayong are required to pay about THB 400 (USD 12.7) as treatment fees.

This project was planned for implementation in three phases. In the first phase (budget of THB 115 million or USD 3.67 million), the facility's infrastructure and a wastewater treatment plant were constructed in an area for sanitary landfill

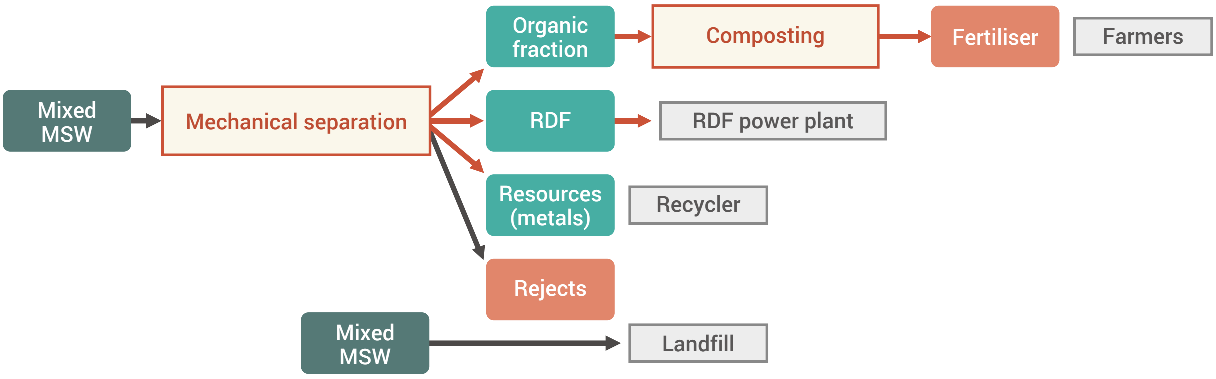


Fig. 10 MBT practices in Rayong, Thailand

(10,800 m^2). The second phase (budget of THB 185 million or USD 5.90 million) was used for construction and to upgrade the mechanical separation process in the facility. A second sanitary landfill (19,200 m^2) was also constructed in this phase. In the third phase (budget of THB 322 million or USD 10.28 million), a composting facility was constructed and the landfill area was extended.

Another important aspect of this project is the cooperative relationship between Rayong PAO and the Global Power Synergy Company Limited (GPSC) to construct the MSW power plant. This project consists of two parts: RDF production and a power plant with the capacity to treat 500 tonnes/day of MSW to produce about 6 to 9 MW of power to sell to the grid.

Implementation and enablers

(a) Social conditions

The Rayong Waste-to-Energy plant is situated in an isolated location in Tambon Nam Khok, Mueang Rayong district with an area of 0.68 km^2. The separation and composting processes were designed to operate under a closed system. The landfill is also operated with an engineered surface covering system. These practices have led to fewer complaints about odour from residents. Discharged effluent from the wastewater treatment facility is also reused in the area, preventing contamination of the environment from the release of polluted water.

(b) Public awareness and cooperation of residents

The Rayong Waste-to-Energy plant receives MSW from most municipalities in Rayong and has had to deal with "Not In My Backyard" (NIMBY) sentiments from the residents in each municipality. Engaging the community and involving the local business sector under the strong leadership of the governing body has raised environmental awareness and fostered a willingness to solve the waste problem with support and cooperation from NGOs and the public sector. Because of the work put in to address the NIMBY issue, the plant was accepted by the residents, who supported the direction promoted by the province.

(c) Institutional aspects

In general, budgeting proposals for system maintenance (or any additional requirements) must undergo a long and detailed process that is not in line with how the project is managed in reality. Fortunately, the Rayong Waste-to-Energy plant was completely managed by Rayong Renewable Energy Ltd. (RY) under a 25-year contract with Rayong PAO. This, coupled with cooperation with the GPSC, allows the Rayong Waste-to-Energy plant to be managed by two private companies, simplifying the management of the budget and operation of the facility when maintenance will be required in the future.

(d) Governance capability

Since the Rayong Waste-to-Energy plant is managed by the private sector, Rayong PAO has been able to address the issue of recruiting an operator to manage the plant in the long term. Together with that, the tipping fee which is collected by the local authority will be discounted as a result of the guarantee to provide MSW to the power plant.

(e) Financial aspects

Rayong PAO entered into a 25-year contract with RY to operate the centre and was able to reduce the budget for recruiting a new operator in the long term. Moreover, the fact that waste can be managed centrally has reduced operating costs for local authorities in the province, while Rayong PAO has been able to decrease tipping fees for local authorities if they are able to guarantee the continuous delivery of MSW to the plant. A budget for constructing a new landfill is not required because the volume of MSW is being reduced through incineration. GPSC also benefits from selling electricity to the grid.

(f) Technological aspects

Integrated solid waste management has been incorporated into several phases because the facility was under construction. The facility has been in operation since 2018, with 500 tonnes/day of mixed MSW delivered to the mechanical separation facility. Recyclable materials (5% of total MSW) are separated out at the start of the separation process. Small particles (about 45% of total MSW) pass through a sieve and are delivered to the composting facility. The remaining large-sized MSW is shredded and incombustible materials (about 20% of total MSW), such as ceramic PVC or metal, are separated and then disposed of at the landfill site. About 30% of total MSW is RDF, which will be used at the power plant to generate 6 to 9 MW of electricity to be delivered to the grid.

5.4 Mitoyo, Japan

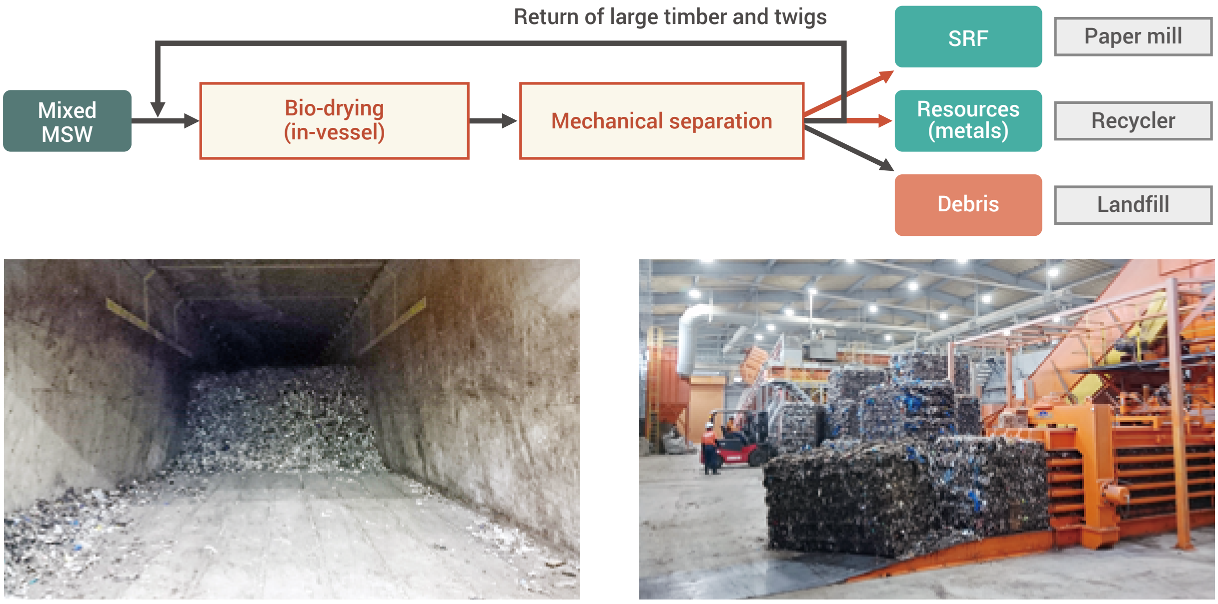
Brief introduction and key points

Mitoyo City has adopted a unique system for municipal waste treatment in Japan (Fig. 11), a country that normally employs the use of mass-burn incineration systems. Municipal waste collected as residual combustible waste (with a daily average of 31.5 tonnes/day) is mixed with wood twigs to increase permeability. A process of in-vessel bio-drying with air circulation and moisture control is used to treat this mixed waste. Six vessels (6 meters wide, 5 meters high and 35 meters long) have been installed in the facility, each with an average bio-drying duration of 17 days. The dried waste is then transferred to the mechanical separation process which divides up SRF components (plastics and paper), large timber and wood twigs, and fine fragmented fractions. Large timber and twigs are then returned to the bio-drying process. SRF fractions are further processed by removing polyvinyl chloride (PVC), which should be avoided for industrial boilers. The product is processed over an average of 13.3 tonnes/day and then sold as feedstock to a solid fuel production company. After SRF is produced, it is utilised in paper mills that are a dominant industry in the region. Stable consumption of SRF is a key factor for success in MBT in this municipality. This case is worth considering as an alternative technology to incineration in the event that a user for SRF has been identified.

Historical background

Mitoyo City was formed in 2006 with the merger of seven towns. It currently has a population of about 63,000. At that time, an incinerator built in 1986 (capacity of 62 tonnes/day x 2 incinerators) was used to treat waste, but the term of use for the land on which it had been built expired in March 2013, leading to its closure. The landfill reached full capacity in 2009 and has since been outsourced.

Between 2010 and 2011, Mitoyo City issued a



In-vessel biodegradation process

SRF produced at Mitoyo

Fig. 11 MBT practices in Mitoyo, Japan

public offering to decide on the type of waste disposal method that would be introduced, arriving at a decision on the use of the system described above soon after. Subsequently, demonstration projects were carried out between 2011 and 2014, and in fiscal 2015 and 2016, Mitoyo City received a subsidy from the Ministry of the Environment. The plant, which actually started operation in April 2017, has been commissioned to Eco-Master, with technology and technical components provided by Shinwasangyo Co., Ltd. under a BOO (Build-Own-Operate) initiative. The plant was constructed at a cost of JPY 1.6 billion (including land costs), with JPY 300 million in subsidies. The city has a 20-year contract with the company, and treatment costs are set at JPY 24.8/kg (not including collection costs).

Implementation and enablers

(a) Social conditions

The reason that this type of system could be introduced to Mitoyo City is because of the presence of manufacturers nearby that mixed about 10% of solid fuel (SRF) with coal to produce paper.

(b) Public awareness and cooperation of residents

Residents had an easier time accepting this system because there were no changes to the existing separation and collection methods used for incineration treatment.

Odour is generally an issue in bioprocessing systems. However, this system adopts the effective method of a biofilter mechanism in which exhaust gas is passed through a layer of wood chips as a way to deodorise the exhaust gas discharged from the bio-drying process. Before exhaust gas is deodorised, it has a strong odour. However, exhaust gas discharged through the filter smells like natural wood, which has eliminated foul odours from garbage around the factory.

(c) Institutional aspects

After the receipt of proposals from businesses with the proprietary technology needed to operate and manage this system, Mitoyo City implemented demonstration projects in cooperation with universities and research institutes. The city was able to move forward with the introduction of a nationally-authorised treatment method by applying for and being approved as a project subsidised by the Ministry of the Environment.

(d) Governance capability

In 2015, Mitoyo City reviewed its basic plan on the disposal of MSW. Recognising that all waste is a resource, the city established a basic philosophy to “build a sustainable community where resources circulate” to promote reuse, recycling and resource recovery as much as possible. Mitoyo City also instituted a basic policy on controlling the generation and emission of waste in a three-way style of cooperation involving residents, businesses and the government, with the aim of promoting the development of a recycling-oriented society and preventing global warming. This plan clearly specified that tunnel composting would be used as a part of the city’s waste treatment practices. Essential to the success of this plan was the strong leadership of the government and partnerships between the public and private sectors.

(e) Financial aspects

The costs of constructing an incinerator with an equivalent treatment capacity are estimated at JPY 4 to 5 billion, an indication that the method employed by Mitoyo City has greatly reduced waste treatment costs for the city.

With the application of a BOO initiative, the city was only required to pay for treatment costs but was not responsible for construction costs.

(f) Technological aspects

This method was originally developed in Europe for composting. In some cases, it may be unavoidable for plastic to be mixed into compost, so it is significant that this method can be used as an alternative technology to incineration that does not target the production of compost.

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About the CCET Guideline series

CCET in partnership with the United Nations Environment Programme (UNEP) - International Environmental Technology Centre (IETC) and the Ministry of Environment, Japan (MOEJ) provides technical assistance to national, sub-national and local governments in developing countries on the development and implementation of waste management strategies. During the implementation of CCET activities, it was found that the issue of waste management is more complex in developing countries, characterised by dramatic urbanisation that has led to an increase in volume and types of waste (including dangerous chemicals and metals, such as mercury, lead, etc.), but with a lack of capacity to sustainably perform proper waste management, including legislation and policies for realistic long-term planning, limited collection and a lack of proper disposal, scavenging issues, poor funding, low public awareness, and other issues. Furthermore, a significant number of inappropriate technologies and equipment has been introduced due to insufficient knowledge on sustainable waste management practices. There is an urgent need to provide accurate information to assist policy-makers and practitioners so that they have a clear and holistic view of all waste management technologies.

The CCET guideline is a series consisting of key technology options that act as pieces of a puzzle to identify an optimal technology mix for addressing the unique challenges faced by governments. It is commonly accepted that there are no universally right or wrong answers to what technology is appropriate for any one region. Rather, solutions need to be developed locally and tailored specifically to local needs and conditions. Citizens and stakeholders need to be involved in designing a diverse set of services which, in turn, needs to be delivered at affordable costs. As with the pieces of a puzzle that form a clear picture when connected, the CCET guideline series offers knowledge-based support for the development of strategies and action plans.

The main purpose of this guideline series is to assist policy-makers and practitioners at the national and municipal levels in selecting appropriate waste management technologies and executing related policies to improve waste management. CCET is focusing on fundamental intermediate treatment technologies, including Composting, Mechanical-Biological Treatment (MBT), Anaerobic Digestion (AD), and Waste-to-Energy (Incineration).

This guideline series:

(1) is a user-friendly, knowledge-oriented product that provides clear, concise and comprehensive points, which makes it easy to identify optimal options at a glance;

(2) has been developed from a "resource perspective" rather than a "waste treatment perspective" based on the concepts of the 3Rs, waste hierarchy and circular economy;

(3) addresses both the physical (technical) elements of collection, disposal and recycling as well as the "soft" aspects of governance, public awareness and participation, and institutional and financial aspects to encourage social engagement; and

(4) is supported by good practices.

United Nations Avenue, Gigiri
PO Box 30552, 00100
Nairobi, Kenya
Tel: +254 (0)20 762 1234
Email: unenvironment-info@un.org
www.unep.org

Economy Division
International Environmental Technology Centre
2-110 Ryokuchi koen, Tsurumi-ku, Osaka 538-0036,
Japan
Tel: +81 6 6915 4581
Email: ietc@un.org
www.unep.org/ietc

National Institute for Environmental Studies
16-2 Onogawa, Tsukuba,
Ibaraki 305-8506,
Japan
www.nies.go.jp/index-e.html

IGES Centre Collaborating with UNEP
on Environmental Technologies (CCET)
2108-11 Kamiyamaguchi, Hayama,
Kanagawa 240-0115,
Japan
Tel: +81-46-855-3840
www.ccet.jp