

Developing an Integrated Environmental Assessment Model for Waste Management System

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ABSTRACT

The paradigm of waste management shifts toward more integrated management, hence a more integrated environment assessment method is emerging to support the strategy formulation. As a systematic and comprehensive environmental management tool, life cycle assessment (LCA) can serve as a keystone of integrated environmental assessment method. But three issues needs improvement: credibility on inventory analysis, limitation of waste stream projection and scenario analysis, and omission of site-dependent information of impact assessment. This study aims at incorporating material flows analysis (MFA) and health risk assessment (HRA) to develop an integrated environmental assessment model for waste management. A model called TWMIEA are developed based on incorporating MFA into scenario analysis and inventory, while the HRA serves as a tool to assess the human toxicity impact. Then the TWMIEA model is applied to evaluation the mid-term waste management policy for Taoyuan County. The result reveals the waste hierarchy can be reexamined by the approach established on integrated waste management.

Introduction

Nowadays, the novel management paradigm called Integrated Waste Management (IWM) had been proposed to replace the traditional waste hierarchy. The main features of IWM are substituting the residue treatment by resource management, and aims to optimize the total environmental benefit by combining different treatment technologies. As the paradigm shifts toward more integrated management, a more integrated environment assessment method is emerging to support the strategy formulation.

An integrated environmental assessment can be defined as “Interdisciplinary process of identification, analysis and appraisal of all relevant natural and human processes and their interactions which determine both the current and future state of environmental quality and resources...thus facilitating the framing and implementation of policies and strategies.” [1]Moreover, Monkhouse and Farmer (2003) propose a conceptual diagram to describe the application of IEA in waste management [2]. From that diagram, two important observations are rise: Life Cycle Approach is the key tool, and a new approach link material consumption and waste stream generation is needed.

As a systematic and comprehensive environmental management tool, life cycle assessment for waste management(WM-LCA) evaluates the overall

environmental burden from the material being discarded to the inert waste placed in landfill or recycle materials and energy utilized by anthroposphere. Unlike LCA for products, the functional unit of WM-LCA is set based on the system input, such as the total amount of municipal waste treated by the waste management system; for the system boundary, WM-LCA can be viewed as the assembly of waste systems for different products; and WM-LCA considers not only the direct environment impact caused by different subsystems, but also the environmental impact of the consumed electricity and fuel production. Moreover, the function of waste management is not limited to treatment of residues, and it also recovers energy and recycles materials. Therefore the avoided environmental impact should be considered by including the raw material and energy production systems.

Since mid-90's, with the integrated waste management emerging, the researchers has started to apply the LCA to waste management policy evaluation. That creates the need for WM-LCA models. A WM-LCA model evaluates the total environment burden of waste's life cycle. Because of the model provides the pollutant emission/resource depletion factors for different subsystems, the user can easily obtain the assessment results by inputting scenario-related parameters, such as waste composition, waste flows, hauling distance, etc. The first WM-LCA model was developed by White et al.

(1995), the so called IWM-1. More WM-LCA models have been developed in the following decade, such as WISARD, ORWARE, ISWM, IWM-2 (a modified version of IWM-1), ISWM-DST, and LCA-IWM. Several issues of concern are associated with these existing WM-LCA models, however:

1. Issue of credibility: The evaluation result of WM-LCA is difficult to verify by measurements. And Winkler had revealed that using ISWM-DST, ORWARE, IWM-2, ISWM, UMBERTO, and ARES, to simulate the same scenarios led to divergent results; for example, the difference of the air and water emissions were as large as 3 times [3]. The inconsistency between existing models indicates that the models and related data should be used carefully.

2. Limitation of impact assessment methods: Most WM-LCA models provide only inventory analysis without impact assessment. On the other hand, the traditional LCA does not incorporate spatial, temporal, threshold and dose-response information in the impact assessment. This diminishes the environmental relevance of the evaluation result, especially for the human toxicity category that deeply concerns the public and is usually deemed as the most important category for waste management [4]. As a result, the effectiveness of the existing WM-LCA models in supporting the policy making is weakened.

3. Limitation of narrow focus on environmental dimension: Basically, LCA is an environment-oriented tool, excluding the economic and societal aspects. But recently, some WM-LCA had incorporated life cycle costing analysis to provide economic information. And the latest WM-LCA model, LCA-IWM, had considered the societal aspect by selecting several criteria that are concerned by the stakeholders and can be evaluated by LCA.

Owing to those limitations, LCA can not serve the only tool of IEA; other environmental management tools are still needed to be incorporated with LCA.

In order to improve the credibility of inventory analysis, and intensify the linkage between consumption pattern and waste stream, the material flow analysis (MFA) is considered. MFA offer systematic assessment of the flows and stocks of materials within a system defined in space and time. It connects the sources, the pathways, and the intermediate and final sinks of a material [5]. There are two main applications of MFA in waste management sector: Investigating the substance management of certain treatment facilities and Calculating and projecting the waste stream. The approach to integrate MFA and LCA has been

presented by ORWARE (ORganic WASTE REsearch), where MFA play as a tool to provide pollutant emission data, and also can be facilitated the task of tracing down specific substances of interest, such as heavy metals flow.

The main objective to integrate the fate and exposure models of health risk assessment (HRA) with the LCA is to seeking the balance between the numbers of processes and pollutants included, and feasibility on health impact. Recently, three operational approaches of integrating HRA and LCA have been developed: human toxicity potential (HTP), Intake Fraction (iF) regression model, and Environmental Damage Estimations for Industrial Process Chain. Among those approaches, HTP are distinguished owing to the high compatibility, and comprehensiveness of substance [6]. Therefore, HTP serve as a basic approach to accomplish the integration of LCA and HRA.

Methodology Development

Above section presents the reason why MFA, HRA should be incorporated with LCA to establish an IEA framework (Figure1). The steps to apply this framework into waste management system to establish the TWMIEA (Integrated Environmental Assessment model for Taiwan Waste Management) model are as follows.

1. Scope and Goal Definition: Since the main function of waste management is to treat the waste effectively and the capacity of each management subsystem should be taken into consideration, the amount of municipal solid waste per year is chosen as the functional unit in this model. The system boundary are designed based on the future scheme of Taiwan waste management policy, thus the collection/ transportation, MRF sorting, bio-waste treatment, recycling, thermal treatment (mass burn and RDF), ash treatment, landfill are included. The scale of time boundary is important for the landfill subsystem. Most emissions of landfill processes come from degradation; hence the amount of pollutants released to the environment varies during a long period. As a result, we choose 100 years as the time boundary for landfill and the other subsystems, implying that the total emission during 100 years will be averaged into one year. Comparing the existing survey and the related WM-LCA models, we define the target pollutants of different subsystems. The categories are divided into air emission, water discharge, soil emission, energy, mineral and water. Total substances included are above 180.

2. Alternatives Formulation and Scenario Analysis: This step is to deal with the input of the model. While

the alternatives are formulated base on policy proposed. But the effect caused by the policy needed to be revealed by scenario analysis. Hence the scenario analysis embeds the waste amount prediction and waste flow identification. Therefore, the statistic method like artificial neural network and regression model provide the former function, but the later function needs MFA. As a result, the inputs of each subsystem under each alternative are calculated.

3. Inventory Analysis: The credibility of inventory databases are improved by two main innovations. The first is substituting the traditional deterministic assessment by probabilistic inventory databases. The approaches of assigning probability distribution forms are mainly based on statistic results for local survey (such as air pollutants emitted by incinerators) and subjective probability transformation by data quality indicators (such as emission from recycling process). The second innovation is integrating MFA to trace the distribution of toxic substance in the hot-spot. Once the first tier evaluation is finished, the MFA should be executed to modify the emission factor of major contributor to the impact.

4. Impact Categories Attribution: The impact categories are considered according to the locally concerned issues and the suitability of characterization. Therefore, our study chooses environment-related indicators from “Taiwan Sustainable Development Indicators” to represent locally concerned issues, and compare them with the widely used impact categories. Furthermore, those impact categories are divided into three groups: site-generic impact, human toxicity and other site-dependent impact, then the emission and resource

consumed data are attributed into three groups. Each group will deal with different impact assessment method reformation.

5-1 Site-generic impact: Global warming, ozone depletion, mineral extraction, energy and water consumption belong to this group. Because of the characterization model of those impacts are well-developed and hold high degree of consensus, hence the latest CFs can be adapted directly.

5-2 Human Toxicity Impact: Not only the HTP applied offer the function of HRA and LCA integration. Owing to the most concerned emissions from waste management subsystems are site-specific. Therefore, “Site-Dependent Human Toxicity Potentials (sd-HTPs)” is adapted to integrate air dispersion modeling, multimedia risk assessment modeling, and population exposure. The sd-HTPs for the heavy metal and dioxins emitted from every incinerator in Taiwan are calculated [7].

5-3 Other site-dependent impact: Acidification, eutrophication, photochemical oxidation, eco-toxicity are the impact categories that should consider the fate analysis and receptor sensitivity. Here, the best available characterization models are chosen to be localized by inputting local parameter. But owing to the time constraint, only the ecotoxicity are localized in this version of TWMIEA.

6 Weighting: In the existing version of TWMIEA, we didn’t provide the weighing factor to aggregate the impact scores into a single evaluation result. But the importance of understandable result is fully recognized, hence the approach to induce objective and subjective method are under development.

7. Interpretation: To provide sufficient and clear

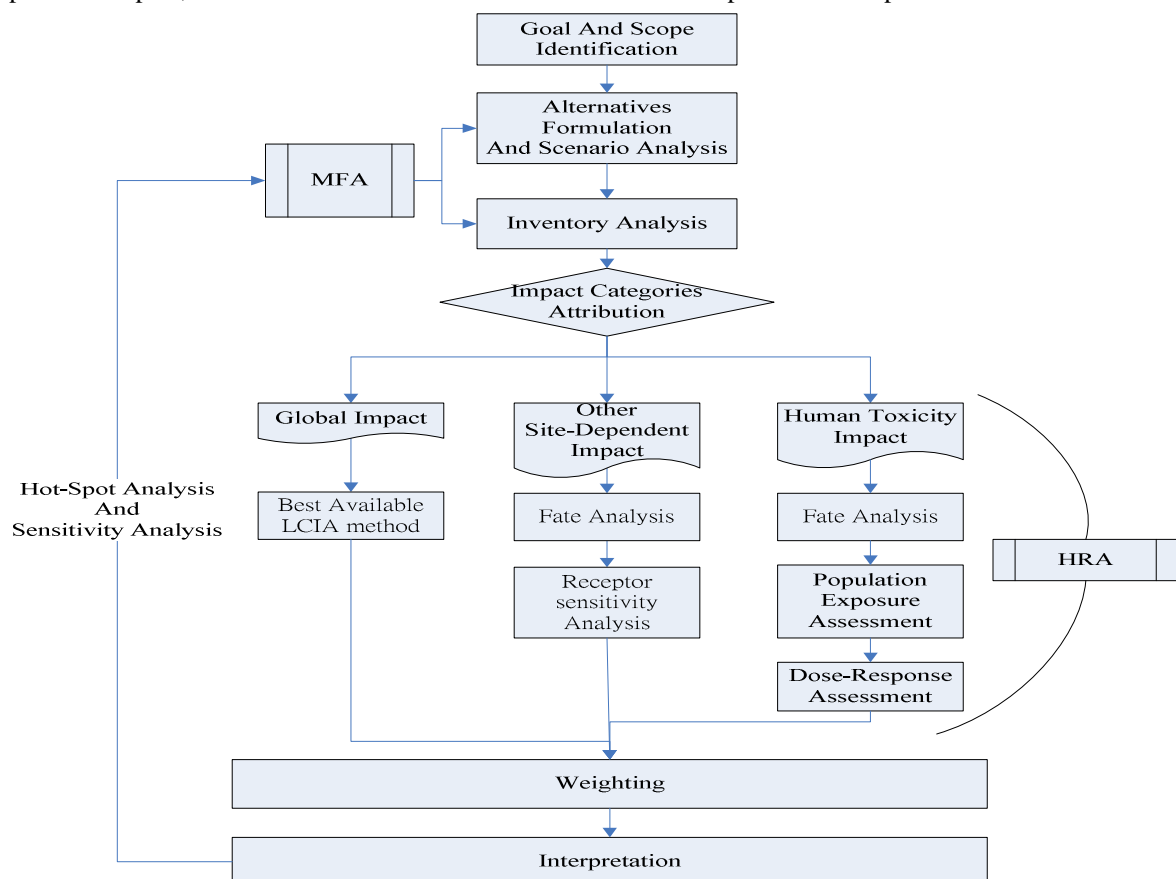


Figure 1 The TWMIEA methodology framework

decision supporting information, the evaluation result are expressed in three forms, impact score, quotients of impact score, and hot-spot analysis. The quotient of impact score equals the ratio between impact score for the certain percentile to the deterministic value of baseline alternative; hence the function of probabilistic inventory databases can be exhibited. The hot-spot analysis recognizes the major substance and process that contribute to certain impact. Combining the hot-spot analysis and sensitivity analysis, then the credibility of evaluation are able to reexamine, and the process and substance needed further evaluated by MFA are also revealed.

Case Study

Taoyuan County, which has a population of over 1.9 million, is the third-largest county in Taiwan. The daily amount of garbage collected is about 1,123 tons, which translates into 0.591 kilograms per capita. Although waste hierarchy is challenged by promising LCA application in waste management, but many NGO still query about this statement. Theoretically,

every treatment technology should be viewed as part of policy, hence we can maximize the environmental benefit by seeking an optimal combination. In fact the administration resource and budget are limited, it hard to consider all possibility, the priority of different treatment combination is still a necessity for decision maker. Hence, base on the waste hierarchy and relative up-level policy instruction, four alternatives are formulated(Table). The baseline is the waste flows in 2005 (Figure2). The target year is 2015.

Inputting the data of table, we can easily obtain the evaluation result by using TWMIEA model. The analysis start from human health related impact categories. Compared to the baseline, there is only Recycle generating more impact than baseline by 2.5 times, while other alternatives lessen the impact. By “hot spot” reorganization, besides Recycle, the arsenic and dioxins emitted to air from incineration are major impact contributors. Hence, the impact score are proportion to the waste incinerated. In addition to that, the hog-feeding process avoided

Table 1 The impact categories of TWMIEA

Impact Categories		Category Indicator	Characterization Model
Human toxicity	carcinogenic	kg-eq Bezene _{air}	CalTOX with local parameters
	noncarcinogenic	kg-eq Toluene _{air}	
Respiratory		kg-eq PM2.5 _{air}	TRACi
Photochemical oxidation		kg-eq NOx _(air)	TRACi
Aquatic ecotoxicity		kg-eq 2,4-D _(water)	TRACi and IMPACT2002+ localized
Terrestrial ecotoxicity		kg-eq 2,4-D _(soil)	
Aquatic eutrophication		kg-eq PO ₄ ⁻	IMPACT2002+
Aquatic acidification		kg-eq SO ₂	IMPACT2002+
Global warming		kgeq CO2 into air	IPCC(2001)
Ozone layer depletion		kg-eq CFCs-11 _(air)	Latest value from WMO
Energy consumption		MJ	CED by Ecoinvent
Mineral extraction		MJ surplus	EcoIndicator 99

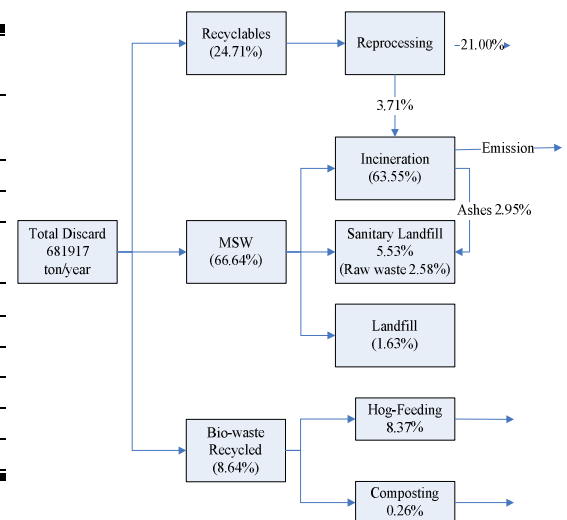


Figure2 Waste Flow of Baseline

Table 2 Alternative Description

Alternatives	Baseline	Business As Usual	Reduction	Recovery	Recycling
Policy	Year 2005, Situation	Follow the mandated sorting policy.	Enforced mandated sorting policy	The ban of landfill. Incineration Improvement	MRF facility setting Replacing hog-feeding by anaerobic digestion.
Effect on WM Stream	None	Total Waste decrease, Recyclables and Bio-waste recycled increases.	Total Waste further decrease, Recyclables and Bio-waste recycled increases significantly.	Total waste amount are as BAU. Only ash sent to landfill. Electricity Recovery Factor of incineration increases.	Total waste amount are as BAU. The impurity rate of recyclable reduce; and 80% of hog-feeding replaced

huge Atrazine emission which is adapted in corn feed production. This is why the Reduction alternative produce only 68% carcinogenic impact compared to baseline. Beside the pollutants mention before, the arsenic emitted to soil bring large influence in Recycle. The emission come from anaerobic digestion and composting processes. In fact, the arsenic are not emitted directly like those from incinerator, the source is "compost". The digestion and composting transform the bio-waste into compost which can utilize in the farm, under this circumstance, the heavy metal consist in the compost are viewed as a kind of soil emission, and the heavy metal containment are adapted from regulations permit values, a more conservative value. If we exclude this soil emission, the impact of Recycle will reduce to only 88% of baseline.

The non- carcinogenic impact shows different trend of carcinogenic impact. No alternative can be environment beneficial, the more you recycle, and the more hazardous that alternative is. The hot spot are lead and copper emitted to air during paper reproducing process. The emission factor used in the model, are adapted from LCA-IWM, which publish that net emission of them are $3.26E-03$ kg/ton and $4.86E-04$ kg/ton, the lead even higher than EF of incineration ($2.03E-05$). And if we replace those value with the emission factor provide by BUWAL($1.5E-05$ kg/ton for lead, 0 for copper), there will become no environment burden of this impact. Under that scenario, lead still play an important role, it generate most avoided impact from electricity recover and offset from incineration and glass recycling.

As for respiratory effect, with the electricity recovery from incineration and raw material avoided by recycling, the waste management system of Taoyuan, provide net gain benefit on this category. The Recycling and Recovery alternative both offer a high pollutant offset than others, but the approaches are divergent. The former reduce the impurity of recyclable, which will led more raw aluminum, tin and glass replaced. The latter increase the electricity recovery, avoided the PM10 and SO_x emitted from coal electricity plants. Like respiratory effect, the photochemical oxidation potential seems cut a large amount by whole waste management system. And as deterministic impact score tell the same ranking amount those alternatives, which imply the more waste incinerated, the more electricity gained, and leads to air quality improved. However, as the information reveals by the probabilistic evaluation result, it is likely the environmental benefit will turn in to burden. The main contributor to this impact and uncertainty is NO_x emitted from incineration. And like mentioned in the previous paragraph, the emission rate still a big issue in here. In some

circumstance, the amount of NO_x emitted won't be enough to compensate the amount avoided by electricity recovery.

The ecological-related groups consist aquatic and terrestrial ecotoxicity, acidification and aquatic eutrophication. The evaluation display that all of the alternatives cause more aquatic eco-toxicity than baseline. The hot spots are air emission of copper and zinc during paper recycling. Thus the discussion of carcinogenic effect can also be adapted here. If the EF are substituted, the result are inversed. That become only Recycle provide generate impact due to heavy metal emitted to soil, the burden offset of other alternative will increase with how much glass are recycled.

The most significant distinguish lie on terrestrial ecotoxicity, Reduction and BAU offer the environment benefit, where as Recovery and Recycle cause burden. But compared to baseline, Recycle are 3 times as hazardous, the reason can be simply understood once we know the major pollutants are nickel. There are three source of nickel, emission from incineration, avoided by glass recycling, and soil emission by compost utilization. As for the Reduction and BAU, the increase of glass recycled accompany with the decrease of waste incinerated, thus the impact are fully compensated. As for Recycle, the significant increase on digestion and composting are the most suitable explanation. If the nickel emission is excluded, the burden is also become benefit. Another issue should be noted; the reduction rate contributes most uncertainty, which means the more successful the mandate waste management policy is, the more likely the ecotoxicity can be minimized.

In this case, the aquatic eutrophication is determined by total Phosphorus emitted from hog-feeding process. Hence if the hog-feeding are replaced by other treatment options, will diminish the impact of this category. The acidification impact depends on the SO₂ offset by electricity recovery and offset. So the ranking are similar to respiratory effect. The uncertainty of this impact is the least one.

The most noticed category of global impact group is global warming. The deterministic values show the whole waste management system can offset large GHGs emission by the electricity recovery and recycling. Comparing Baseline, Reduction and BAU, strongly support the following slogan: "Reduction and Recycle will make Earth cooler!" And the difference between BAU, Recycle and Recovery, show the easier direction to assist further GHGs reduction, to improve the electricity recovery rate will be more beneficial than MRF setting. Another information revealed by the probabilistic result is, the possibility that baseline alternative will generate positive emission is 81%. Although the deterministic

show the Reduction avoided the highest GHGs emission, but the possibility of positive emission are 12%, while Recovery only holds 9%.

From this case, there are several observations can be made:

1. The waste hierarchy paradigm is still effective at certain circumstance: If we exclude the conservative assumption of compost utilization. The evaluation result can be support the Reduction owns the high priority to Recycling and Recovery. Actually, Reduction need the least infrastructure, the cost might be also less than other options. Reflected to the waste policy in Taiwan, the necessity of MRF and RDF building needs to be reconsidered.
2. The measurement and regulation of incineration should be reform: The main uncertainty of human health related impacts are

related to the emission rate. In some impact, a well-controlled emission rate of incinerator may turn the burden into environmental benefit. It provides a clue to rethink the existing emission standard and measurement requirement of incinerator. That is the not only concentration are important, the total amount emitted are more crucial.

3. The EF of recycling process hold significant influence on evaluation result: In the common sense, the recycle process should be least site dependent process in waste management system. But as this case shows, the EF adapted will shock the evaluation. Hence, we will suggest the researchers of WM-LCA field and authority, should execute a detail inventory analysis that focus on the main recycle subsystems, such as paper, metals and glass.

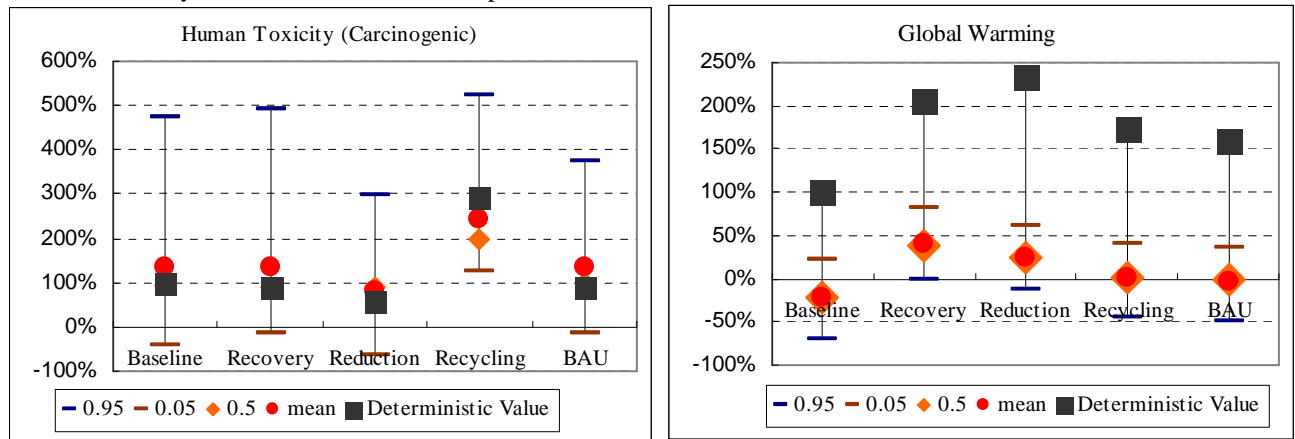


Figure 3 The partial evaluation result presented by quotients of impact score

Conclusion and Future Work

This study provides a practical tool to realize the IEA of waste management. With the effort spent on impact assessment, the site-dependency of impact categories are discussed, moreover the human toxicity and eco-toxicity are localized. Hence that development will serve as the foundation of Taiwan LCIA method. Incorporating HRA and MFA into LCA, not only overcome the limitations of WM-LCA model, also offer the methodology reformation, like sd-HTP.

The future directions of the TWMIEA reformation include completing the impact assessment innovation, which means the site-dependent categories localization and weighting factor determination. Also the function of MFA will be expanded to provide the specific indicator such as MIPS, to facilitate de-toxic and examine the efficiency of material recycling. Therefore, the paradigm shift of Taiwan waste management policy will be implemented.

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