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EVALUATION OF MUNICIPAL WASTE LANDFILLING USING THE TECHNOLOGY QUALITY ASSESSMENT METHOD

Evaluation of waste landfilling technologies performed has been presented with the technology quality assessment method. This method enables complex (technological, environmental, economic) comparisons of technological options including waste disposal involving emission (I) or utilization (II) of biogas, landfilling of treated waste from the mechanical-biological treatment (MBT) unit with emission of biogas (III) and treatment of waste in MBT unit plus option III (IV). Results of the technology quality calculation for options I–IV are 1971, 1709, 1170, 1748 points, respectively. If the technology quality of option I is 100%, utilization of biogas or introducing the MBT system improves technical quality by 11–13%.

1. INTRODUCTION

Landfills are a component of regional waste management systems. The operation time of landfills depends on the function of the system, the method of converting waste before its disposal, and the capacity allocated for waste storage. The landfill operation time will also affect the impact of the landfill on the environment. Several methods for assessing the impact of landfills on the environment have been developed. These methods typically involve both environmental and economic calculations [1–3]. An effective technological and environmental evaluation would not only allow the impact on the environment to be determined but would also provide information concerning the entire

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ecological balance of the environmental management system, which allows the interactions between various technologies to be compared.

The objective of this study is to provide evaluation of municipal solid waste landfill technologies by the technology quality assessment method, which has been applied to assess the technical processes. In this method, the impact of technology on the environment is assessed based on the material balance of the process being evaluated. Calculations for four different municipal waste landfilling technologies were performed, and the mechanical and biological waste treatment technologies were valuated.

The methods reported in the literature for evaluating ecological or economic impacts of municipal waste management systems [1–11] include environmental impact assessment (EIA), environmental performance evaluation (EPE), life cycle assessment (LCA), environmental option assessment (EOA), risk assessment (RA) and cost-benefit analysis (CBA).

2. METHOD FOR ASSESSMENT OF THE TECHNOLOGY QUALITY

The environmental and economic indicators for evaluating the waste management processes can serve as a basis of a comprehensive technology quality Q_T assessment, which qualitatively describes the technologies being compared [1, 2, 4]. The method consists of summing the partial indicators of the technology quality, Q_J, [12, 13]:

$$Q_T = \sum_J Q_J \tag{1}$$

where Q_T is the technology quality, Q_J – individual partial indicators of technology quality obtained from the following formula:

$$Q_J = A\frac{F}{W_C} \tag{2}$$

where, F is the indicator being analyzed (Q_{ED}, Q_E, Q_M, Q_K, Q_O, Q_H, respectively); W_c is the value criterion and A is the degree of importance of the value of these indicators, respectively. Q_{ED} represents global indicators for cumulative risks that assess the ecological quality, Q_E is the energy consumption, Q_M – the material consumption, Q_K – the production cost, Q_O is the odor emission level, and Q_H is the noise emission level.

The assessment of the environmental effects (Q_{ED}) of various technologies for the management of waste was performed based on the process analysis in terms of the cumulative calculation. The starting point for the analysis is the material balance, which evaluates the effects of the emissions of dust and gases into the air and the consequences of the release of solid and liquid waste from the waste management technologies. For the evaluation, a technology grid of the process being assessed is established and complemented with the values of emissions and releases from the operations and processes of individual units. For the purposes of this method, the following concepts have been introduced: the index of cumulative risk *WS*, which is the sum of the emissions or releases of one type of substance during the processes, and the index of cumulative risk $WS \times K$, which considers the toxicity coefficient *K* [1, 4] (Table 6). The toxicity coefficient *K* is a numerical determiner of toxicity that characterizes a given substance. The toxicity coefficients are defined as follows [1, 2, 4, 14]:

- for emissions of dust and gases, *K* is defined as the quotient of emissions fee per 1 t of a given substance and per 1 t of sulfur dioxide emitted into the air,
- for waste landfilling, *K* is defined as the quotient of landfilling fee per 1 t of a given substance and the minimum landfill disposal fee of the waste listed in the relevant regulations [14],
- for liquid waste release, *K* is defined as the quotient of release fee per 1 t of a given substance and per 1 t of sulfates.

The sum of the cumulative risk indicators for all phases of the evaluated waste management technology and all the emissions from the processing of waste constitute the global cumulative risk index, *GWS*:

$$GWS = \sum_{f=1}^{n} WS \times K \tag{3}$$

The energy consumption index, Q_E, was defined as the sum of GJ of energy used in all phases of the processing or disposal of waste, $f = 1, ..., n$, in all the individual technologies that were investigated.

$$Q_E = \sum_{f=1}^{n} E_f \tag{4}$$

where E_f is the energy consumed during individual stages of the process.

The material consumption, Q_M, is defined as the sum of consumption indices of 1 kg of all raw materials required to process 1 t of waste in all phases of waste disposal or processing, $f = 1, ..., n$.

$$Q_M = \sum_{f=1}^{n} M_f \tag{5}$$

where M_f is the quantity of material consumed during individual stages of the process.

Another indicator for describing the technology quality is the Q_K index, which determines the cost of waste disposal or processing in all phases of the waste disposal or processing, $f = 1, ..., n$, and is estimated based on the cost of operating the technology processes in relation to 1 t of waste.

$$Q_K = \sum_{f=1}^{n} K_f \tag{6}$$

where K_f is the cost of individual phases of the process.

The odor, Q_O, and noise, Q_H, emission indices of the individual installations are determined by comparing the two installations according to the assumptions provided in [2, 4]. The result of the calculations is the technology quality, Q_T, which is a dimensionless indicator that allows various landfilling technologies to be compared.

Selecting the technology options for the evaluation and calculation assumptions. Calculations of the technology quality of four municipal solid waste landfilling options, including the mechanical and biological treatment (MBT), were performed to evaluate the following municipal waste management options [5, 6, 8]:

- I. Waste landfilling with biogas emission.
- II. Waste landfilling that utilizes the biogas for energy production.
- III. Landfilling of treated waste from the MBT unit with biogas emission.
- IV. Mechanical and biological treatment of waste in the MBT unit plus option III.

Evaluation of MBT is based on a typical solutions used in modern facility. First the wastes are mechanically separated into light fraction of high calorific waste used for refuse derived fuel (RDF), and the remaining heavy fraction for treatment or storage. The fractions separated in the mechanical part are further treated: metals are recycled, waste with high calorific fractions are separated for RDF, inert materials and waste are disposed, whereas waste of low calorific fraction is further processed in a biological stabilization process, which takes about 3 weeks, and then, in subsequent weeks, maturation takes place. Input data are taken from the literature [15, 16].

For each of the options, the global indicators of cumulative risk were calculated separately for dust and gas emissions, wastewater release, and waste disposal. During the calculations, the following assumptions were made based on the data from the operation of the system or based on [6, 17]:

- The quantity of landfill gas of 160 m^3/t of waste contained 59.4% of CH_4, 39.6% of CO_2, and 1% of other contaminants,
- Gas consumption in the operation phase was 30%, and after the closure of the landfill, it was 70%; for the calculations, an average of 50% gas consumption from 160 m^3/t of waste was assumed; for option II, electricity was produced from the recovered landfill gas.
- The quantity of landfill gas after MBT was 30 m^3/t of waste.
- Density of methane was 0.71424 kg/m^3.

- The quantity of leachate was 25% of annual precipitation (precipitation assumed at the level of 719.2 $(\text{dm}^3\cdot\text{m}^2)$/year).
- The density of compacted waste was 1.5 t/m^3.
- The quantity of waste deposited after MBT was 710 kg/t waste input.
- Concentrations of contaminants in the landfill gas were as in the last column of Table 1.

Table 1

Contaminants in the landfill gas

Contaminant	Concentration [mg/m^3]		
	After [17]	After [18]	Assumed value
1.1.1-trichloroethane	1.0×10	2.3	6.1
1.1-dichloroethene	2.5×10		2.5×10
1.2-dichloroethane	5.0×10^{-1}		5.0×10^{-1}
Benzene	8.0	3.5	5.8
Butane		1.2×10	1.2×10
Cadmium	5.6×10^{-3}		5.6×10^{-3}
Carbon tetrachloride		3.0×10^{-1}	3.0×10^{-1}
Chlorine (Cltot)	6.5×10		6.5×10
Chlorobenzene		1.0×10^{-1}	1.0×10^{-1}
Ethyl chloride		1.3×10^{2}	1.3×10^{2}
Trichloromethane	1.0×10	1.0	5.5
Chrome	6.6×10^{-4}		6.6×10^{-4}
Dichloromethane	8.0×10	3.0	4.2×10
Dichlorodifluoromethane (CFC-12)	4.0×10	6.2×10	5.1×10
Ethane		2.4×10	2.4×10
Ethyl benzene	2.0×10	1.2×10^{2}	6.9×10
Fluorotrichloromethane (CFC-11)	1.0×10		1.0×10
F-total	1.3×10		1.3×10
Hexane	3.6	1.1×10	7.1
Hydrogen sulfide	2.0×10^{2}		2.0×10^{2}
Mercury	4.1×10^{-5}		4.1×10^{-5}
Lead	5.1×10^{-3}		5.1×10^{-3}
Polychlorinated biphenyls (PCBs)	1.6×10^{-3}		1.6×10^{-3}
Pentane		6.0	6.0
Propane		5.0	5.0
Tetrachloroethylene	1.0×10	7.1×10	4.1×10
Toluene	1.0×10^{2}	3.1×10^{2}	2.0×10^{2}
Xylene (sum of isomers)	7.7×10	4.0	4.0×10
Trichloroethylene	2.0×10	9.1×10	5.6×10

- Concentrations of contaminants in the exhaust gas of the electricity generator were as in the last column of Table 2.

Table 2

Contaminants in the exhaust gas of the electricity generator

Contaminant	Concentration [mg/m^3]				
	After [19]	After [20]	After [21]	After[22]	Assumed value
1.1.1-trichloroethane	8.8×10^{-4}				8.80×10^{-4}
1.2-dichloroethane	8.3×10^{-4}				8.30×10^{-4}
Benzene	5.2×10^{-3}				5.20×10^{-3}
Carbon monoxide		6.5×10^{2}	1.3×10^{3}	1.0×10^{3}	9.83×10^{2}
Chlorine (Cl_{tot})	1.1×10^{-1}			0.0	1.10×10^{-1}
Chloroform	8.3×10^{-4}				8.30×10^{-4}
Chrome	1.1×10^{-6}				1.10×10^{-6}
Dichloromethane	8.3×10^{-4}				8.30×10^{-4}
Ethyl benzene	1.8×10^{-2}				1.80×10^{-2}
Fluorine (F-total.)	2.1×10^{-2}				2.10×10^{-2}
Hydrogen chloride		3.0×10	5.5×10^{-3}	4.9	1.16×10
Hydrogen fluoride		1.0	3.5×10^{-3}	2.1	1.03
Hydrogen sulfide	3.3×10^{-1}		8.3×10^{-2}		2.07×10^{-1}
Mercury	6.9×10^{-8}				6.90×10^{-8}
NMVOC			2.3×10	5.0×10	3.65×10
Nitrogen oxides	1.0×10^{2}	5.0×10^{2}	1.2×10^{3}	8.1×10^{2}	6.53×10^{2}
PAH			3.0×10^{-1}	1.4×10^{-2}	1.57×10^{-1}
Lead	8.5×10^{-6}				8.50×10^{-6}
PCB	2.7×10^{-6}				2.70×10^{-6}
Dioxins	1.0×10^{-7}	1.0×10^{-8}	1.2×10^{-6}	7.1×10^{-9}	3.29×10^{-7}
PM10			6.8	1.8×10	1.24×10
Sulfur dioxide	2.5×10	2.3×10^{2}	2.1×10^{2}	2.8×10^{2}	1.86×10^{2}
Tetrachloroethene	3.3×10^{-4}				3.30×10^{-4}
Trichloroethene	5.0×10^{-3}				5.00×10^{-3}
Vinyl chloride	2.0×10^{-3}				2.00×10^{-3}

- Average composition of the leachate during the operation of a section of the landfill (period A), after closing the quarter (B), and 20 years after closing the quarter (C) are given in Table 3. Twenty years is the average time for the emission of biogas from the landfill.

Details concerning the energy consumption in the landfill are given in Table 4. Energy consumption in the MBT technology, including both mechanical sorting and biological stabilization, falls within the range from 40 to 70 kWh of electric energy (55 kWh/t assumed) and ca. 1 dm^3 of oil/t of waste input [8, 12].

The consumption of raw materials for reclamation was considered (estimated as 15% of the mass of waste deposited). For options III and IV (with MBT), 71% of the initial waste mass was assumed. The estimation of the costs of the MBT and landfilling treatment are given in Table 5. The discount rate used in the calculation was 5%; however, the authors decided to omit this information, as they considered the most important data to be those concerning the production costs, which are shown in the tables. The introduction of discounted costs renders the analysis more complex.

Table 3

Assumed average composition of the leachate
during the operation of a quarter (period A), after closing the quarter (B),
and 20 years after closing the quarter (C) [9, 17]

Parameter	Leachate composition [mg/dm^3]			Reduction of contamination after period C [%]
	Period A	Period B	Period C	
pH	7.40	7.60	–	–
BOD$_5$	1529.00	275.00	68.80	75.00
COD	3147.50	1585.00	396.30	75.00
Ammonia	502.50	555.00	416.30	25.00
Nitrates (NO_3^-)	5.60	12.00	6.00	50.00
Nitrites (NO_2^-)	0.35	0.50	0.30	50.00
Total nitrogen	508.40	567.50	425.60	25.00
Total phosphorus	3.00	3.00	2.30	25.00
AOX	2.30	1.51	0.40	75.00
Chlorides	1717.50	1760.00	880.00	50.00
Sulfate (SO_4^{2-})	122.00	93.00	46.50	50.00
Sulfite (SO_3^{2-})	5.80	2.00	1.00	50.00
Sodium	970.00	905.00	452.50	75.00
Potassium	1065.00	695.00	347.50	75.00
Magnesium	247.50	145.00	72.50	75.00
Calcium	420.00	325.00	162.50	75.00
Boron	5.90	5.60	2.80	75.00
Manganese	54.40	1.10	0.30	75.00
Iron	32.50	9.90	2.50	75.00
Arsenic	0.02	0.04	0.01	75.00
Cadmium	0.01	0.00	0.00	75.00
Chrome	0.19	0.16	0.04	75.00
Copper	0.39	0.06	0.00	75.00
Mercury	50.0	0.00	0.02	75.00
Nickel	0.17	0.14	0.00	75.00
Lead	0.11	0.07	0.03	75.00
Zinc	1.30	0.53	0.01	75.00

The landfilling cost of option I was assumed to be approximately € 84/t of waste based on the above data. This landfilling cost already represents the assumed European standard. The cost of the MBT was estimated to be € 29. The energy received from the landfill gas was assumed to be 5 kWh/t of waste.

Table 4

Energy demand of the landfilling process [8, 9]

Subject	Demand
Electric energy in landfilling process, kWh/t of waste	2.00
Electric energy for gas capture, kWh/m^3 of gas	0.15
Electric energy leachate treatment, kWh/m^3 of leachate	22.00

Table 5

MBT and landfilling cost per 1 ton of waste per 1 ton of waste
for household waste in Warsaw [9]

Indicator	MBT cost	Cost of landfilling
Initial venture capital (depending on the throughput), €	125	68
Project depreciation, €/year	10	5
Operating and maintenance cost, €/year	28	3
Lifetime end cost, €	6	3
Equivalent annual discounted lifetime end cost, €/year	0.2	0.1
Total annual discounted cost, €/year	38	8

The level of odor emission was estimated based on the assumption that there is a 100% elimination of odor during the thermal waste processing. For the MBT processes, the odor emission level was estimated using the same method as for municipal waste landfilling processes. If maximum value of the odor emission is 100%, the level of odor emission is 80% of this value, which indicates that 20% of the emitted odors could be eliminated as a consequence of the reclamation of specific parts of the landfill [2, 6, 7]. The emission of odors during landfilling is mitigated by, among other approaches, the exploitation of biogas. Therefore, for the landfills that utilize the biogas, the emission of odors was estimated to be 56% of the maximum value, which is consistent with previously reported data [7, 8]. This value is 30% lower than that in the landfills that do not utilize the biogas. In landfills, noise emission is only generated by the machinery used for the spreading and compacting of waste. The level of noise emission was established as 50%, options I and II) when the operating time was estimated to be 12 h per day. For MBP, the number of noise-emitting devices is considerable. The noise-emission level was estimated to be 35% for option III. For option IV, the noise emission level was estimated to be 65% [2, 6, 7].

3. RESULTS AND DISCUSSION

Table 6 presents the results of the calculation of the GWSe – global index of cumulative risk of emission into the air for option I. This indicator was calculated for each of the options in addition to the wastewater release GWSr, and waste dumping GWSs. Due to the considerable number of calculations, only the final results from the calculations of other GWS indicators, based on [7] are given in Table 7.

Table 6

Calculations of the cumulated risk index GWSe for the emissions into the air from option I. Landfilling with biogas emission

Process stages – emissions – dust and gas [kg/t] of dumped waste					*WS*	*K*[b]	*WS*×*K*[c]	GWSe
Risk contaminant	Unloading, transport, storage	Landfill leveling	Landfill reclamation	Landfill gas emission				
Inert dust	0	0	0.5	0	0.5	2.60	1.30	189.702242
Landfill dust	2.5	2.5	0	0	5	3.90	19.50	
Methane	0	0	0	67.882	67.882	2.01	136.44	
1.1.1-trichloroethane	0	0	0	9.76×10^{-4}	9.76×10^{-4}	1365	1.332	
1.1-dichloroethene	0	0	0	4.00×10^{-3}	4.0×10^{-3}	1365	5.460	
Benzene	0	0	0	9.28×10^{-4}	9.28×10^{-4}	62.4	0.0579	
Butane	0	0	0	1.92×10^{-3}	1.92×10^{-3}	1.06	0.00203	
Chlorine	0	0	0	1.04×10^{-2}	1.04×10^{-2}	9.22	0.09589	
Ethyl chloride	0	0	0	2.08×10^{-2}	2.08×10^{-2}	9.22	0.19178	
Trichloromethane	0	0	0	8.80×10^{-4}	8.8×10^{-4}	1365	1.2012	
Dichloromethane	0	0	0	6.72×10^{-3}	6.72×10^{-3}	1365	9.1728	
Dichlorodifluoro-methane (CFC-12)	0	0	0	8.16×10^{-3}	8.16×10^{-3}	1365	11.1384	
Ethane	0	0	0	3.84×10^{-3}	3.84×10^{-3}	2.01	0.00772	
Ethyl benzene	0	0	0	1.10×10^{-2}	1.10×10^{-2}	10.40	0.11482	
Fluorotrichloro-methane (CFC11)	0	0	0	1.60×10^{-3}	1.6×10^{-3}	1365	2.1840	
Fluorine	0	0	0	2.08×10^{-3}	2.08×10^{-3}	9.22	0.01918	
Ebony	0	0	0	1.14×10^{-3}	1.136×10^{-3}	10.40	0.01181	
Hydrogen sulfide	0	0	0	3.20×10^{-2}	3.2×10^{-2}	9.22	0.29504	
Pentane	0	0	0	9.60×10^{-4}	9.6×10^{-4}	2.01	0.00193	
Propane	0	0	0	8.00×10^{-4}	8.0×10^{-4}	2.01	0.00161	
Tetrachloroethylene	0	0	0	6.56×10^{-3}	6.56×10^{-3}	20.56	0.13487	
Toluene	0	0	0	3.20×10^{-2}	3.2×10^{-2}	9.22	0.29504	
Xylene (sum of isomers)	0	0	0	6.40×10^{-3}	6.4×10^{-3}	9.22	0.05901	
Trichloro-ethylene	0	0	0	8.96×10^{-3}	8.96×10^{-3}	20.56	0.18422	
Vinyl chloride	0	0	0	3.20×10^{-3}	3.2×10^{-3}	156.0	0.49920	

[a] *P* – production rate (quantity of disposed/processed waste).

[b] *K* – toxicity index.

[c] *WS*×*K* – cumulated risk index considering the toxicity index. *WS* – cumulated risk index, *ZS* – cumulated risk, GWSe – global index of cumulative risk of emission.

Table 7

List of the GWS indices for different municipal waste landfilling options

Landfilling option	GWSe	GWSr	GWSs	GWSsum
I – with biogas emission	189.702242	0.031549	29.030	218.764
II – with biogas utilization	153.312578	0.031549	29.030	182.374
III – landfilling of waste from MBT with biogas emission	84.138341	0.031549	20.611	104.781
GWS for MBP	76.8	0.0	0.0	76.8
IV – MBP + option III				181.581

The GWSsum indicator is calculated as follows:

$$\text{GWSsum} = \text{GWSe} + \text{GWSr} + \text{GWSs} \tag{7}$$

The technology quality, in points, was calculated for individual partial indices from Eq. (2). The sum of the indices (Eq. (1)), for individual options provides the comprehensive quality index, Q_T, for each of the analyzed options. The assessment of the comparative technology quality considered the following values of partial quality indices: environmental global indicators of cumulated risks, Q_{ED}, production cost, Q_K, energy consumption, Q_E, material consumption, Q_M, odor emission level, Q_O, and noise emission level, Q_H. Table 8 provides the values of partial indices F of the technology quality for individual analyzed options.

Table 8

Comprehensive assessment of technology quality
of the options presented. List of indices value F

Indices F of partial technology quality Q_J	Indices for the assessed technology options Landfilling options			
	I	II	III	IV
$Q_{ED} = \text{GWS}_{\text{sum}}$	218.764	182.374	104.781	181.581
Q_E, GJ/t	0.0312	0.0288	0.0312	0.0429
Q_M, kg/t	1150	1150	816	816
Q_K, €/t	84	84	60	89
Q_O, %	80	56	56.8	80
Q_H, %	50	50.174	35.5	65.1

Table 9 provides the results of calculations of the technology quality Q_T, the municipal waste landfilling options were calculated using Eq. (2). According to the method of calculation, a lower summarized point score corresponds to a greater technology quality. The quality indicators of the individual technologies were also compared in percentages by assuming that the highest calculated indicator corresponds to 100% (in this case, for option I of municipal waste landfilling, the indicator equals 100%). The W_c indicators of the individual partial indices were calculated by dividing the maximum value of the ratio of the partial indices (*F*) by 100.

Table 9

Comprehensive assessment of the options presented.
Results of calculations of technology quality Q_T

Indices *F* of partial technology quality Q_J (cf. Table 8)	Partial technology quality assessment		Partial technology quality [points] $Q_J = F/(W_cA)$			
			Landfilling options			
	W_c	Priority A	I	II	III	IV
Q_{ED} = GWS	2.2	10.0	1000.0	833.7	479.0	830.0
Q_E, GJ/t	0.0429	3.0	2.2	2.0	2.2	3.1
Q_M, kg/t	11.5	3.0	300.0	300.0	212.9	212.9
Q_K, €/t	0.89	4.0	299.1	299.1	213.6	316.8
Q_O, %	1.0	4.0	320.0	224.0	227.2	320.0
Q_H, %	1.0	1.0	50.0	50.2	35.5	65.1
Technology quality Q_T [point]			1971.2	1708.9	1170.4	1747.9
Effect in comparison to option I			100.0	86.7	59.4	88.7

The analysis of all the environmental indicators (of global indicators of cumulative risks) for individual municipal waste landfilling options indicate that the option based on burning of the landfill gas in an electricity generator reduces the environmental risk by 13.3% compared to the landfilling of untreated waste. The option of landfilling the waste after it is biologically and mechanically treated reduces the environmental risk by 40.6%; however, considering the global indicators of cumulative risks for the mechanical and biological system, the gain is minimal, approximately 1.0%. Therefore, the most environmentally beneficial and relatively simplest solution is the installation of electricity generators in landfills.

Cost estimations indicate that, after treatment in the biological and mechanical system, the cost of landfilling pretreated waste is reduced if the waste generated during the process is utilized. The odor emission level from the landfill is considerable regardless of the utilized landfilling option. Furthermore, in this case, the burning of landfill gas is beneficial because it significantly reduces odor emissions. The noise emission levels from the landfills or mechanical and biological treatment systems are relatively high.

4. CONCLUSIONS

The assessment of the technology quality is the method which allows one to compare the municipal waste landfilling technologies. The results of the comparison of options I–IV are 1971, 1709, 1170 and 1748 points, respectively. Assuming that the landfilling quality in a typical landfill (option I graded 1971 points) is 100%, the modification of landfilling technology (by burning of the landfill gas or the introduction of the mechanical and biological processing system) improves the landfilling technology by 11–13%.

The assessment of municipal waste landfilling using the technology quality method allows a quantitative comparison of various waste management systems, which primarily considers the indices of environmental impacts of the technology.

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