International Journal of Energy and Power Engineering
2021; 10(1): 20-29
http://www.sciencepublishinggroup.com/j/ijepe
doi: 10.11648/j.ijepe.20211001.13
ISSN: 2326-957X (Print); ISSN: 2326-960X (Online)

Comparison of the Energy Recovery Potential Using Life Cycle Assessment of Municipal Solid Waste of Abidjan (Côte d'Ivoire)

Adjoumani Rodrigue Kouakou[1], Ehouman Ahissan Donatien[1], Kouadio Marc Cyril[2]

[1]Laboratoire de Thermodynamique et Physico-Chimie du Milieu, UFR Sciences Fondamentales et Appliquées, Université Nangui Abrogoua, Abidjan, Côte d'Ivoire

[2]Institut de Recherche sur les Energies Nouvelles, Université Nangui Abrogoua, Abidjan, Côte d'Ivoire

Email address:

adjoumanro@gmail.com (A. R. Kouakou)

To cite this article:

Adjoumani Rodrigue Kouakou, Ehouman Ahissan Donatien, Kouadio Marc Cyril. Comparison of the Energy Recovery Potential Using Life Cycle Assessment of Municipal Solid Waste of Abidjan (Côte d'Ivoire). *International Journal of Energy and Power Engineering*. Vol. 10, No. 1, 2021, pp. 20-29. doi: 10.11648/j.ijepe.20211001.13

Received: February 23, 2021; **Accepted**: March 11, 2021; **Published**: March 26, 2021

Abstract: The development of societies and industrial progress cannot be achieved without the use of electricity. The growing demand for energy and the degradation of the environment by current sources force us to look for other methods to produce it. The production of renewable energy from landfill waste reduces the environmental problems caused by the combustion of coal, oil and natural gas. Therefore, in this work, life cycle assement is used to compare the different energy recovery options of four solid waste management systems with each other and to assess the corresponding carbon credit. The four management systems are: landfilling (scenario S_0), landfilling with energy recovery (scenario S_1), incineration combined with anaerobic digestion with energy recovery in both cases (scenario S_2) and incineration with energy recovery (scenario S_3). The assessment showed that scenario S_2 is the best waste management option for energy production with an energy potential of 890.9 GWh/year, which corresponds to 11% of the Côte d'Ivoire's net electricity production in 2015. In addition, this scenario has led to a better reduction in methane emissions with a carbon credit of USD 12168200 for the total amount of waste managed in one year. However, scenario S_1 is the wrong option in terms of energy production with an energy potential of 232.2 GWh/year corresponding to 3% of the Ivory Coast's net electricity production in 2015. Regarding the potential reductions in CO2equivalent emissions, those of scenario S1 are the lowest with a carbon credit of US$ 12,025,343. From the point of view of the production of clean and green energy, the voice to be followed for an optimal MSW management technique in Abidjan is the anaerobic digestion of the organic fraction, the incineration of the fuel fraction, followed by the landfilling of the residues.

Keywords: Biogas, Renewable Energy, Life Cycle Assement, Solid Waste

1. Introduction

In developed and developing countries, human activities lead to the production of large quantities of waste. This waste is a source of pollution because of its presence in the environment. In addition, this waste can be recovered into energy, thus reducing its impact on the environment. Electricity is an essential component of the development of societies and industrial progress. The growing demand for energy and the degradation of the environment by current sources force us to look for other methods to produce it. The production of energy from landfill waste reduces the environmental problems caused by the combustion of coal, oil and natural gas [1]. Thus, there is a pressing need to exploit the energy potential of municipal solid waste (MSW) through strategies for its treatment. There are different methods of solid waste treatment. However, given the heterogeneity of this solid waste, it is not easy to determine the best way to manage this waste [2]. The proportion of each waste stream in the total amount of municipal solid waste varies according to several factors [3]. Waste streams classified as organic can be burned or composted, while waste streams classified as inorganic cannot. Organic waste streams include paper, plastics, textiles, wood, food waste and garden waste, while inorganic waste streams include glass and metals. As a result, waste treatment strategies have been studied by researchers around the world [4-7]. In addition, the comparison of the influence of various parameters on energy potential using life cycle analysis (LCA) revealed that the composition of MSW is a key factor that directly affects energy potential from different MSW management strategies. Even if the same treatment is used, the energy potential differs in the differences in MSW components and operating parameters [8, 9].

About 65% of the MSW generated in Abidjan (Côte d'Ivoire) is disposed of in the Akouédo landfill, and the remaining 35% is burned uncontrolled or forgotten in public places. This practice is a danger not only to the health of the population of Abidjan and the environment, but is also a potential source of greenhouse gases with serious environmental consequences. Although waste-to-energy (WtE) technologies have been developed in several countries around the world, in Côte d'Ivoire, there are almost no studies to this effect. Thus, information on the subject on the potential contribution of MSW to the profile of the Côte d'Ivoire 's energy supply is limited.

The objective of this study is to apply the Life Cycle Assessment (LCA) methodology as an analytical tool to compare the different energy recovery options of four solid waste management systems with each other and to assess the corresponding carbon credit. Thus, the LCA methodology based on ISO 14040-43 and Eco-indicator 99 was used.

2. Methodology

2.1. Site Description

The district of Abidjan consists of 13 municipalities, covers an area of 2.119 km^2, is the largest in Côte d'Ivoire and is located at 5 ^{0}20'11'' north and 4^0 01'36" west. The mass of the waste generated was evaluated using the most recent population data [10] from National Institut of Statistic (INS) and projected to 2017 based on 4.1% growth rate and the per capita waste generation of 0.77kg/capita /day [11]. The composition of MSW of the district is showed in figure 1 [11]. It is assumed to be the same during the evaluation period (2017-2036).

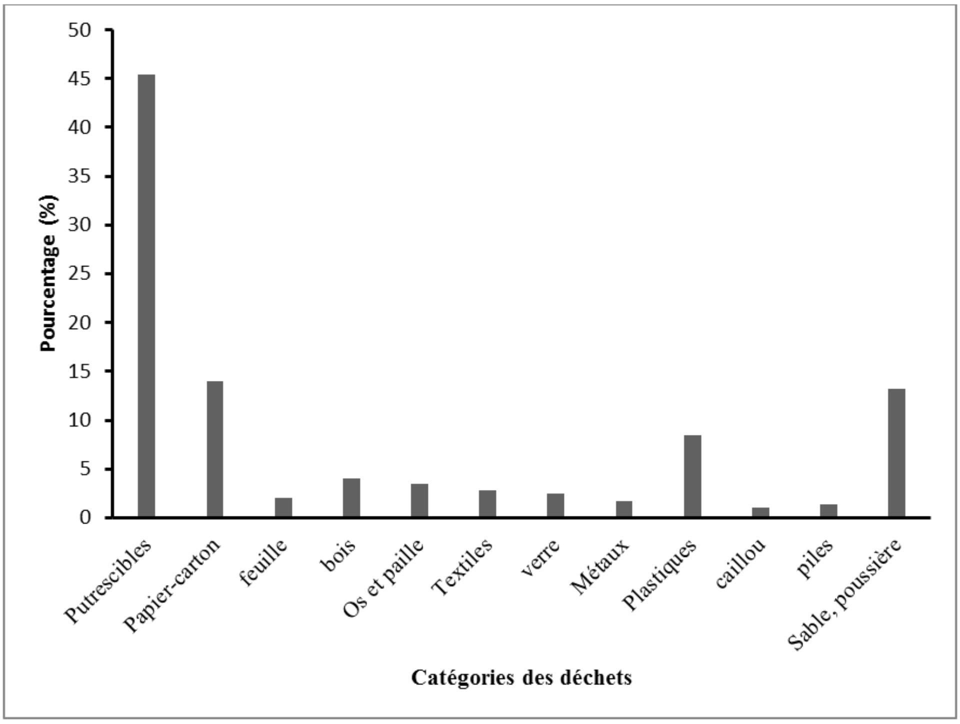

Figure 1. *Annual average of the waste composition in Abidjan.*

2.2. Physical and Chemical Characteristics of the Waste

Waste samples were collected according to MODECOM for five independent days from the contents of collection trucks arriving at the landfill site [11]. The analyses were carried out according to standard methods AFNOR [12]. Thus; the total humidity H, the volatile dry matter content (VM) (drying and combustion at 550°C) and the carbon/nitrogen ratio (C/N) were determined [12]. Total humidity and dry matter content were determined by drying in an oven for 24 hours. As for the volatile dry matter content, it was determined by calcination at 550°C for 4 hours. The carbon C content was determined from the following theoretical formula:

$$C = \frac{VM}{1,724} \quad (1)$$

The nitrogen (N) was obtained by hot mineralization (300°C) of the organic matter in a sulphuric acid medium.

2.3. Lower Calorific Value of Waste

The LCV (kcal/kg) of the waste was calculated from the following equation [12]:

$$LCV_{WasteINC} = \left(CR_{pa}P_{pa} + CR_{te}P_{te} + CR_{pl}P_{pl} + CR_{wo}P_{wo} + CR_{fo}P_{fo} + 44P_{mi}\right)\left(\frac{(100-H)}{100}\right) - 6H \quad (2)$$

P_{pa}: paper and cardboard (%);
P_{te}: textiles (%);
P_{pl}: plastics (%);
P_{wo}: woods (%);
P_{fo}: food waste (%);
P_{mi}: other combustibles component (%);
H: moisture content;
CR_{pa} (35,19), CR_{te} (36,24), CR_{pl} (71,17), CR_{wo} (48,26), CR_{fo} (42,21) and CR_{mi}(44) are the regression coefficients for $P_{pa}, P_{te}, P_{pl}, P_{wo}, P_{fo} et\ P_{mi}$. respectively.

2.4. Estimation of the Mass of Waste Generated and Collected

The mass of municipal solid waste (MSW) generated was estimated using demographic data from 2008 to 2014 and extrapolated to 2017. The population growth rate and the specific daily waste production are 4.1% and 0.77 kg/inhabitant/day respectively [10; 11]. The population of Abidjan is about 4.8 million in 2014 [10]. In Abidjan, only 65% of the waste produced is collected and deposited at the disposal site [11]. Thus, the mass of waste going to landfill (M_F) was obtained by the following equation:

$$M_F = t_c \times M_T \quad (3)$$

t_c is the waste collection coverage rate (0.65);
M_T (t/year). is the total mass of waste generated per year.
M_T is calculated from the following relation:

$$M_T(t) = n_{ja} \times P(t) \times w_c \quad (4)$$

P(t) the expected population for the year in question (from 2017 to 2036), taking into account a growth rate r of 4.1%;
w_c is the waste generation rate which is of 0.77kg/capita/day;
n_{ja} is the number of days in a year (365).
Thus, the expected population $P(t)$ was determined by the following equation:

$$(t) = P_0(1 + r)^t \quad (5)$$

r : growth rate;
P_0 : Population of Abidjan in 2017 taken as a reference;
t: time of extrapolation.
Finally, the mass of waste going to landfill is calculated by the following relation:

$$M_F(t) = tc \times n_{ja} \times w_c \times P_0(1 + r)^t \quad (6)$$

The amount of MSW composition ($M_{F(t)i}(t/year)$) that could be utilized for different technologies such as landfill gas to energy (LFGTE), anaerobic digestion (AD) and Incineration (INC) was estimated using the following relation:

$$M_{F(t)i} = M_{F(t)} \times f(i) \quad (7)$$

With:
i: the type of waste-to-energy technology which could be Landfill Gas to Energy (LFGTE), incineration (INC) or Anaerobic Digestion (AD)
f: the organic fraction of the waste composition that goes into the specific technology option;
t: the number of years of calculation;
$M_{F(t)}$: mass of waste in landfill.
Putrescible fraction of waste composition were allocated to AD technology. Combustible portion of the waste stream was used for INC system while combination of combustibles and putrescible/yard waste fractions were considered for LFGTE technology. The results of fraction of waste composition for each scenario are presented in Table 1.

Table 1. *Fraction of MSW used for each scenario.*

Scenarios and remaining waste	MSW fraction used by scenario (%)	
Scenario S_0: Landfilling without energy recovery	f_{GDC}=80,09	
Scenario S_1: Landfilling with energy recovery	f_{GDC}=80,09	
Scenario S_2: Incineration combined with anaerobic digestion	f_{INC}= 34,67 f_{DA}= 45,42	$f_{INC}+f_{AD}$=80,09
Scenario S_3: incineration	f_{INC}= 80,09	
Remaining waste	recyclable= 4,25	recyclable+ f_{Inerte}=19,91

2.5. Functional Unit

In this work, the functional unit is the annual average waste managed in tonnes (t), from 2017 to 2036. Average annual waste managed over a period of 20 years without including recyclable and inert components of MSW is calculated by Eq. (6).

$$M_{FU(i)} = \frac{\sum_{t=1}^{n} M_F(t) \times f(i)}{n} \quad (8)$$

$$M_{FU(i)} = 1240799.21t$$

2.6. Life cycle Assessment (LCA)

LCA is a systematic methodology for an environmental comparison between energy production technologies from waste developed by different scenarios of current and future waste management strategy [12]. ISO 14040/43 and Eco-indicator 99 are used in this study.

2.6.1. Analysis Assumptions

To perform the life cycle analysis, five hypotheses were taken into account. These are:

1. the exclusion of the objectives the emissions due to the transport and the waste collection of this study because they are the same for all the scenarios. Only emissions relating to the activity time of the landfill are considered [14---16];
2. an assumed zero charge for all environmental impacts

due to a product before it is converted into waste;
3. Excluding energy and emissions during the construction of waste treatment facilities;
4. the performance of all scenarios over a period of 20 years (2017-2036);
5. Excluding the effects of carbon storage from landfills (carbon sequestration) in all scenarios.

2.6.2. Estimation of the Electrical Energy Potential Generated Using Different Waste-to-Energy (WtE) Technologies

(i) Biogas to Energy (LFGTE)

The electrical energy potential generated by LFGTE technology depends largely on the methane content of the biogas generated, which in turn depends on the amount of waste buried [8]. In this analysis, the LandGEM 3.02 model was used to estimate the amount of biogas generated [17]. In this estimate, the specific k and L_o values for the Akouédo landfill were used.

For this estimate, the values used for the recovery rate and oxidation factor are 75% and 10% respectively [18-20].

The electrical energy potential (kWh/year) $E_{P(LFGTE)}$ is obtained from the methane content of the biogas generated according to the following relationship:

$$E_{P(LFGTE)} = \frac{LHV_{CH4} \times 0{,}9 \times Q_C \times \eta}{3{,}6} \quad (9)$$

3.6 is the conversion factor of MJ to kWh;

η is the electrical conversion efficiency which has a value of 33% for an Internal Combustion Engine (ICE) of[21, 22];

LHV_{CH4} is the lower calorific value of methane which is 37.2 MJ/m^3;

0.9 is the proportion of methane emitted;

Q_C is the average flow rate of methane collected per year (m^3 /year).

The average methane flow rate collected per year was estimated according to the following formula:

$$Q_c = \lambda \times Q_g \quad (10)$$

λ: biogas recovery rate (75%);

Q_g: average methane flow rate generated.

$$Q_g = \frac{\sum_{i=1}^{n} Q_{CH_4}(i)}{n} \quad (11)$$

$Q_{CH_4}(i)$: flow rate of methane generated in year i;

n: number of years considered (20 years).

The methane generated is estimated according to the USEPA LandGEM [12] mathematical model (see Eq.(12)).

$$Q_{CH_4} = \sum_{k=1}^{n} \sum_{j=0.1}^{1} kL_0 (\frac{M_{LFGTE}}{10})\, e^{-kt_{ij}} \quad (12)$$

with Q_{CH_4} = annual production of CH_4 (m^3/year), t = 1-year time increment, n= (year of the calculation) –(initial year of waste acceptance), j = 0.1-year time increment, k = methane generation rate or constant ($year^{-1}$), L_o = potential methane generation capacity (m^3/t), M_{LFGTE} is the annual waste landfilled (t/yr) (see Eq.(5)).

In the LandGEM model, degradable organic carbon (DOC) is used in the Eq (13) to calculate the methane generation potential (L_0)[23].

$$L_0 = MCF.DOC.DOC_F.\, F.\frac{16}{12} \quad (13)$$

$$DOC = 0.4P + 0.15K + 0.3W + 0.24T \quad (14)$$

$$DOC_F = 0.014\, T_{emp}(°C) + 0.28 \quad (15)$$

Where MCF is the methane correction factor assumed to be 0.8 (uncontrolled discharge), DOC_F is the assimilated DOC fraction assumed to be 0.77 [24]. Temp is the temperature of the discharge area. F is the methane fraction by volume in the landfill gas that is assumed to be 0.5, P is the MSW paper fraction, K is the MSW kitchen waste fraction and W is the wood/leaf fraction MSW and T is the textile fraction of MSW.

The production rate (k) is determined according to the method proposed by Aguilar et al [25].

$$k = \sum_{i=1}^{10} (\%r_i \times vp) \quad (16)$$

$\%r_i$: percentage of waste in each category;

v_p: value of k predetermined by the MBM 2.0 model in each degradation category.

(ii) Incineration with Energy Recovery (INC)

The incineration unit has a capacity that is based on the average annual amount of waste generated. The pollution load is assumed to be zero for waterborne pollutants. The efficiency of the electricity recovery unit is 20% [18, 22, 26].

The electrical energy (kWh/year) E_{INC}, generated from the useful heat produced in a steam turbine, has been estimated by the relation 17:

$$E_{P(INC)} = \frac{LHV_{wasteINC} \times M_{INC} \times \eta_{inc}}{3{,}6} \quad (17)$$

$LHV_{wasteINC}$ (MJ/kg): lower calorific value of waste;

η_{inc}: conversion efficiency;

M_{FINC} (tonnes/year) is the average annual mass of waste;

$$M_{FINC} = \frac{\sum_{t=1}^{n} M_{FINC(t)}}{n} \quad (18)$$

$M_{FINC(t)}$: mass of waste (tonnes) used for incineration calculated using equation 7;

n: duration of the project t (20 years).

(iii) Anaerobic Digestion (AD)

The potential for electricity generated with this technology was estimated using equation 19:

$$E_{P(AD)} = \frac{(V_{CH_{4th}} \times \eta \times LHV_{CH_4} \times M_{F(AD)})}{3{,}6} \quad (19)$$

With,

$V_{CH_{4th}}$ (m^3/tonnes): actual volume of methane in biogas;

η: electrical efficiency of the generator supplied with the generated biogas (0.26) [27];

LHV_{CH_4}: lower heating value of methane which is 37.2 MJ/m^3;

$M_{F(AD)}$ (tonnes/year): average mass of raw material used for AD.

The theoretical volume of methane $V_{CH_{4th}}$ was estimated using the model proposed by Salami et al. [28]. According to this model, the moisture content M (%) of the solid waste is given by the following relation:

$$M = \frac{a-b}{a} \times 100 \quad (20)$$

a: initial mass of waste (kg);

b: mass of dry solid waste (kg).

The mass of dry solid waste b is given by the following relation:

$$b = \sum\left(\frac{100-C_i}{100}\right) \times d_i \quad (21)$$

C_i: typical moisture content for each waste category (Table 2);

d_i: mass of each category of waste per 100g of waste (kg).

Table 2. *Typical composition of solid waste [28].*

category	humidity (%)	Density (kg/m^3)	C	H	O	N	S	Ash
fermentable	25	240	48,5	6,5	37,5	22,2	0,3	5,0
plastics	2	65	60,0	7,2	22,80	-	-	10
paper	6	85	43,5	6,0	44,0	0,3	0,2	6,0
glass	2	195	-	-	-	-	-	-
sand	20	130	-	-	-	-	--	-
Ash	8	480	26,3	3,0	0,5	0,5	0,2	68,0

This estimate takes into account the volume v_i of each category of the solid waste sample. To calculate this volume v_i the following relation is used:

$$v_i = \frac{m_i}{l_i} \quad (22)$$

m_i: mass of each category of solid waste;

l_i: density of each solid waste category.

The total volume v of the waste sample is estimated from the following formula:

$$v = \sum v_i \quad (23)$$

The mass m of the solid waste sample is estimated by the relation:

$$m = \sum m_i \quad (24)$$

Thus, the density of the sample of solid waste is estimated by the formula:

$$l = \frac{m}{v} \quad (25)$$

In addition, the mass of oxygen required for complete aerobic stabilization of solid wastes ($C_fH_gO_hN_{i(s)}$) is estimated using the following equation:

$$C_fH_gO_hN_{i(s)} + \frac{4f+g-2h-3i}{4}O_{2(g)} \rightarrow fCO_{2(g)} + \frac{g-3i}{2}H_2O_{(l)} + iNH_{3(g)} \quad (26)$$

If ammonia (NH_3) is oxidized to nitrate the required oxygen mass is determined from the following equation:

$$NH_{3(g)} + 2O_{2(g)} \rightarrow H_2O_{(l)} + HNO_{3(g)} \quad (27)$$

To estimate the theoretical methane volume that could be expected from anaerobic digestion, the following equation is used:

$$C_fH_gO_hN_{i(s)} + \frac{4f-g-2h-3i}{4}H_2O_{(g)} \rightarrow \frac{4f+g-2h-3i}{8}CH_{4(g)} + \frac{4f-g+2h+3i}{8}CO_{2(g)} + iNH_{3(g)}\ ) \quad (28)$$

In practice, a part of the waste is intended for the synthesis of the cellular tissues of the organism which influences the microbial decomposition. The actual volume of biogas is about 85% of the calculated theoretical value.

The average mass of raw material used for AD was estimated by equation 29:

$$M_{F(AD)} = \frac{\sum_{t=1}^{n} M_{FAD(t)}}{n} \quad (29)$$

$M_{FAD(t)}$: mass of the proportion of waste (tonnes) used for AD. It was calculated using Equation 7;

n: durée du projet (20 ans).

2.6.3. Scenarios Studied

(i) Scenario 0: Landfill Without Biogas Recovery (S_0)

This is the baseline scenario where all waste fractions, with the exception of recyclable materials (metals, glass), are buried at the landfill without energy recovery (Figure 2).

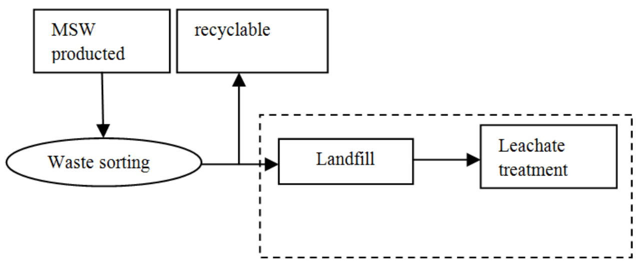

Figure 2. *Simplified flowsheet and boundary settings for scenario 0.*

The equivalent CO_2 emission (CH_4) is calculated by multiplying the annual CH_4 emission by 25 as methane is 25 times the global warming potential of CO_2[29]. Thus according to the Eq.(30):

$$E_O(\text{kgCO}_2\text{eq/year}) = GWP_{CH_4}.\,0.9\ M_{CH_4}.1000 \quad (30)$$

$$M_{CH_4}(\text{Mg/an}) = 6.67\ Q_g.\,10^{-4} \quad (31)$$

$$Q_g = \frac{\sum_{i=1}^{n} Q_{CH_4}(i)}{n} \quad (32)$$

$$Q_c = \lambda Q_g \quad (33)$$

where E_0 is the CO_2 equivalent of CH_4 released without energy conversion, M_{CH_4} is the mass of CH_4 gas, Q_g the average methane generated per year (m^3/year), GWP_{CH_4}. ($kgCO_2$/kg GHG) is global warming potential of CH_4 and 0.000667 is a conversion factor from m^3/yr to Mg/yr, n is the number of years considered (20 years), λ is the collection efficiency (λ = 75% [8]) and Q_c is the average of methane collected per year (m^3/year) with a factor of oxidation of 10% [8] relative to the coverage of the landfill.

(ii) Scenario 1: Landfill with Energy Recovery (S_1) (See Figure 3)

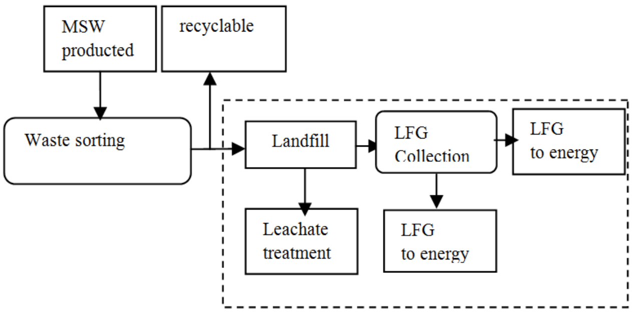

Figure 3. *Simplified flowsheet and boundary settings for scenario 1.*

The CO_2 emission in this case is not taken into account for the GWP because it does not have a fossil origin; the rest (25% of the biogas) is supposed to be released directly into the atmosphere. Thus, the CH_4 equivalent to CO_2 (CO_{2eq}) emitted E_{LFGTE} is calculated according to the relation:

$$E_{LFGTE}(kgCO_2\ eq/an) = GWP_{CH_4} \times 0.25 \times M_{CH_4} \times 1000 \quad (34)$$

(iii) Scenario 2: Incineration and Anaerobic Digestion (See Figure 4)

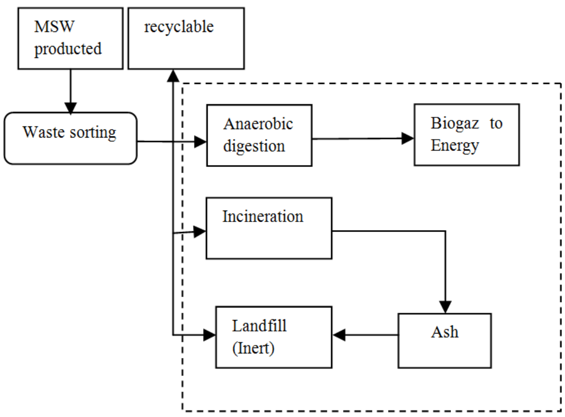

Figure 4. *Simplified flowsheet and boundary settings for scenario 3.*

To obtain the total emissions through this scenario, it is necessary to sum the emissions due to waste incineration and those due to anaerobic digestion.

(a) Emissions from the incineration plant

The incineration plant used is the massive combustion plant designed with a capacity in agreement with the annual average of the waste mass (Eq. (35)) [8].

$$M_{FINC} = \frac{\sum_{t=1}^{n} M_{FINC(t)}}{n} \quad (35)$$

where $M_{FINC\ (t)}$ is the quantity of waste (t) used for incineration during period t (20 years) determined according to Eq. (5). $M_{FINC\ (t/yr)}$ is the average annual mass of incinerated waste.

The GHG emission by incineration technology (E_{INC}) is calculated by Eq. (36) [30]:

$$E_{INC} = E_{CO_2} + \sum_{h=1}^{n} E_h \quad (36)$$

$$E_{CO_2} = FC.\ M_{FINC}.\ \alpha.\frac{M_{CO_2}}{M_C} \quad (37)$$

$$E_h = EF_h \times GWP_h \times PCI_{déchetINC} \times M_{FINC} \times \%F_{nonbiogenic} \quad (38)$$

where FC is the fossil carbon component, h is the GHG concerned, M_{CO_2} = 44 kg/mole, M_C = 12 kg/mole, α = oxidation factor (α = 100% [31]), EF_h is emission factor of the GHGs (30 kg/TJ and 4 kg/TJ for CH_4 and N_2O respectively [30]), $F_{nonbiogenic}$ is the fraction of anthropogenic component in the waste stream and $LHV_{wasteINC}$ is the lower heating value of the waste obtained in (2). The CO_2 emission of biomass (paper, wood, food and other biodegradable components) from waste is not considered because it is assumed to be biogenic.

(b) Emission of the anaerobic digestion facility

In this case, only the putrsecible fraction of the waste is put in a digester for biogas. Here it has been assumed that biogas lost by leakage is 5% [31, 32]. Thus CH_4 emitted into the air because of leakage (E_{MAD}) is determined by Eq. (39):

$$E_{MAD} = 0.05.GWP_{CH_4}.V_{CH_{4actuel}}.\rho_{methane}.\ M_{FA}D \quad (39)$$

$$M_{F(AD)} = \frac{\sum_{t=1}^{n} M_{FAD(t)}}{n} \quad (40)$$

where $\rho_{methane}$ is the density of CH_4, (0.717 kg/m^3) [17], $V_{CH_{4actuel}}$ is the actual volume of CH_4 produced by the anaerobic digester. It is calculated according to the method used by Salami L et al. [28], $M_{F\ (AD)}$ (t/year) is the average mass of feedstock placed in the digester according to Eq. (30) and $M_{FAD\ (t)}$ is obtained by Eq. (5).

(iv) Scenario 3: Incineration with Energy Recovery (See Figure 5)

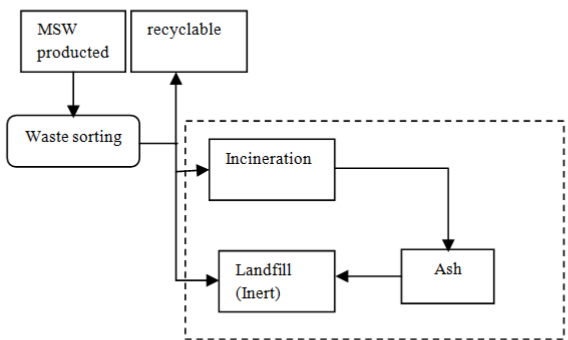

Figure 5. *Simplified flowsheet and boundary settings for scenario 4.*

In this case, all waste except recyclables and inerts are incinerated to generate electricity while the remaining ash is dumped. The emissions due to this ash are not taken into account in the calculations. GHG emissions for this technology were calculated according to Eq. (36).

3. Results and Discussion

3.1. Physical Characteristics of Municipal Solid Waste

The organic fraction and the inorganic fraction are respectively 80.09% and 19.91%. The organic fraction, the highest, is about 4/5 of the mass of waste. The putrescible fraction (composed mainly of food waste) is the largest in the organic waste received (47.42%). Recyclable waste such as paper and cardboard, plastic, glass, textiles and metals accounts for 30% of MSW. The high proportion of organic waste in Abidjan is due to the eating habits of populations. For example, Abidjan people would typically consume unprocessed and unpackaged foods. This waste can be removed by anaerobic digestion.

The proportions of organic waste and recyclable waste in this study were compared to those of other countries (Table 3).

Table 3. *Proportion of recyclable and organic MSW in some countries.*

Country	Recyclables (%)	organic putrescible (%)	References
Côte d'ivoire	30	47,42	this study
Hongary	29	36,00	[33]
Slovakia	38	31,00	[33]
Tunisia	24	65,00	[34]
China	21	60,00	[35]
France	58	29,00	[34]
Greece	47	39,00	[34]

For the proportion of MSW that can be recycled, the value obtained in this study is higher than those determined in some countries such as Hungary [33], Tunisia [34] and China [35]. However, the proportion of recyclable MSW in this study is lower than those determined in other countries such as Slovakia [33], France [34] and Greece [34]. Recyclable waste represents a smaller fraction of MSW in developing countries compared to cities in developed countries, unlike China [13]. The composition of the MSW in Abidjan is dominated by a high content of putrescible organic matter higher than that of France [34], Slovakia [33], Hungary and Greece [33].

In contrast to Côte d'Ivoire, the high proportion of MSW that can be recycled in developed countries is due to increased use of paper and plastic with electronic media (television, radio, etc.) in these countries [35]. It is well known that MSW in developing countries are made up of more biodegradable waste than recyclable waste [36].

3.2. Physicochemical Characteristics of Waste

The high moisture content of MSW (43%) is due to the fact that this waste consists mainly of food waste. Anaerobic digestion (AD) is appropriate for this type of waste, while incineration (INC) suitable for combustible waste (plastic, paper, etc.) is also possible [37]. Munipal solide waste (MSW) with a moisture content of less than 45% and a volatile dry matter (VM) level above 40% are suitable for thermochemical conversion. In addition, MSW with a lower moisture content to 45% and a VM rate lower than 15% are suitable for thermochemical conversion (incineration, pyrolysis, gasification). For MSW having a C/N ratio between 25 and 30, a higher moisture content to 50% and a VM rate greater than 40%, it is preferable to apply anaerobic digestion [37]. Fuels like diesel are needed to burn these MSW. This is the case of MSW incineration in Thailand, where the largest fraction of MSW is food waste with a moisture content of 40-60% [38]. The combustion of this waste without the use of fuels is difficult. Since incineration is a type of mass combustion, the separation of waste according to its heating capacity and moisture content should improve combustion and reduce fuel consumption [38].

3.3. Assessment of the Lower Heating Value of Municipal Solid Waste

The value of the lower heating value (LHV) of municipal solid waste (MSW) is 1763,199 kcal/kg or 7377,225 MJ/t (according to equation 2). Incineration of these MSW with energy recovery is possible [39]. In fact, when the lower heating value of municipal solid waste is greater than 1700 kcal/kg, their incineration with energy recovery is possible [39]. Also, to maintain the combustion of municipal solid waste in a self-sustaining combustion state, the LHV of municipal solid waste must be greater than 4960 MJ/t. Failing this, a supplement of fuel mixed with the waste would be necessary for their combustion [40]. Therefore, the combustion of Abidjan's municipal solid waste can be done under self-sustaining combustion conditions.

The lower calorific value of municipal solid waste from this study were compared with those of other studies (Table 4).

Table 4. *LHV of MSW in selected developing countries.*

City or country	LHVof MSW(kcal/kg)	References
Abidjan(Côte d'Ivoire)	1 763,199	This study
Dhaka (in Bangladesh)	550-850	[41]
Delhi (in India)	800-1 100	[42]
Amman (in Jordan)	2 747	[43]
Mostaganem (in Algeria)	1 700	[39]
Ouagadougou (Burkina Faso)	4 780	[44]

The LHV of MSW in this study is higher than that found in other developing country studies such as Bangladesh [41], India [42], and Algeria [39] (Table 4). However, it is low compared to that found in other studies in developing countries such as Jordan [43] and Burkina Faso [44].

The annual mass of waste generated as well as the physico-chemical characteristics of the waste are important in the estimation of the volume of biogas generated from mathematical models. The volume of biogas is essential in estimating the energy potential of a landfill.

3.4. Fraction of Municipal Solid Waste Used by Scenario

Table 1 summarizes the MSW fractions used for each scenario. An analysis of this table shows that the fraction of MSW used for all different scenarios is 80.09%. The remaining one is 19.91% with 15.66% inert MSW and 4.25% MSW recyclable. The fraction of incinerated MSW (f_{INC}) ranges from 34.67 to 80.09%. As for the buried MSW fraction (f_{LFGTE}), it is 80.09% for the S_0 and S_1 scenarios and 47.42% for the S_3 scenario. The fraction of MSW used for anaerobic digestion (f_{AD}) is 45.42% for the S_2 scenario.

The high fraction of MSW used for these different scenarios could be justified by the composition of MSW. The MSW consist mainly of organic waste (71.59%) and plastic waste (8.5%), as shown in Figure 1. The f_{INC} fraction used in the S_3 scenario would be related to fuels (plastics, paper-cartons, wood, textile, bones and straw) contained in MSW (32.67%) as shown in Figure 1. The variation in f_{INC} would be due to leaves and fermentables with fractions of 2% and 45.42% respectively. When considered as fuels, f_{INC} increases from 32.67% to 34.67% and then to 80.09%. The f_{AD} fraction of 45.42% used for anaerobic digestion is justified by the fact that only fermentable MSWs were used for anaerobic digestion (Table 1).

3.5. Potential of Electricity Production

Figure 2 describes the energy potential of the different scenarios with energy recovery studied. Scenarios S_1, S_2 and S_3. These results suggest that the best option for MSW management for power generation is S_2 (891 GWh), followed by S_3 (509 GWh) and scenario S_1 (232 GWh).

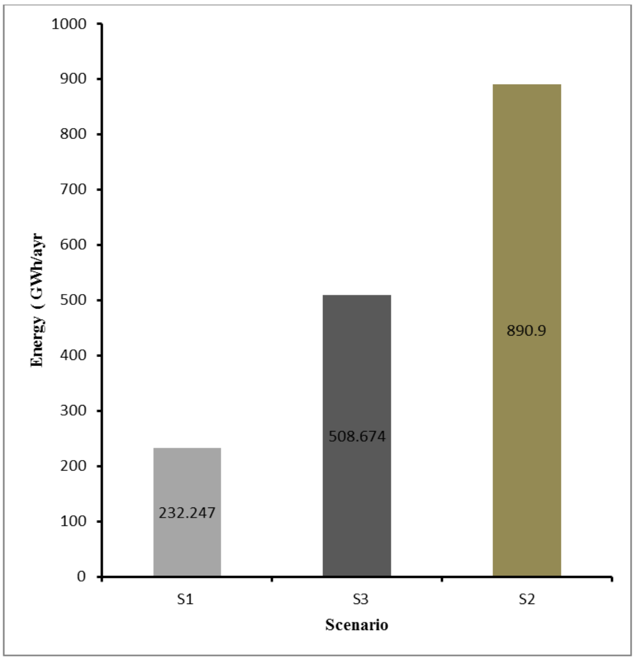

Figure 6. *Energy potential of different technologies.*

The high energy potential of the S_2 scenario would be due to the combination of anaerobic digestion and incineration. This could be explained by the presence in MSW of plastics, certain fuels (paper-cardboard, wood, textile) having high calorific values and a large quantity of fermentable with a high biodegradability. In addition, incineration is the best management option for MSW for energy production [45]. The low energy potential observed for scenario S_1 could be explained by the presence in MSW not only of material that is difficult to biodegrade, such as textiles, but also plastics. Plastics are stable; they do not degrade and therefore do not contribute to the production of methane in landfills. These energy values for these different scenarios could be used to provide about 3% to 11% of 2015 net electricity production in Côte d'Ivoire according to the CIE (Ivorian electricity company) annual report in 2015. Taking into account the tariff electricity of 66.96 F CFA/kWh (US $ 0.12) this corresponds to a gain of between 15.53 billion F CFA and 59.7 billion F CFA (US $ 27 million - US $ 103 million). It should be noted that the scenario S_0 is a technology without energy recovery. It therefore has a zero energy potential.

3.6. Carbon Credit

The potential reduction in CO_2 equivalent emissions that would no longer be released to the atmosphere for the scenarios S_0, S_1, S_2 and S_3 are presented in Table 5. This CO_2 equivalent reduction is zero for the base scenario S_0. For scenarios S_1, S_2 and S_3, these potential reductions are between 1093kt and 1106kt of CO_2 equivalent. Thus the corresponding credits have values between USD $ 12,025million and USD $ 12,168million US $ per year. This calculation is based on the results of Pathak et al [46] who reported an average cost of USD $ 11.00 CO2e/tonne on the carbon market.

Table 5. *Carbon credit corresponding to each scenario.*

Scenarios	The potential reduction in CO_2 equivalent emissions(kt CO_{2e})	Carbon credit (US $)
S_0	0	0
S_1	1093,213	12 025 343
S_2	1106,200	12 168 200
S_3	1095,093	12 046 023

4. Conclusion

Four scenarios (S_0, S_1, S_2 and S_3) of the MSW treatment systems in Abidjan are analyzed using LCA to compare their energy recovery potential and the resulting carbon credit. The results indicated that:

a. Scenario S_0 (landfill), the baseline scenario, has the highest methane emission. It has no energy potential nor carbon credit;;

b. Scenario S_2 (anaerobic digestion combined with incineration with energy recovery) gives the best option in terms of energy production with an energy potential of 890.9 GWh/year. This scenario also corresponds to the largest reduction in CO_2equivalent emissions with a carbon credit of US$ 12168200;

c. In terms of energy production, scenario S_1 (landfill with energy recovery) is the least interesting with an energy potential of 232,2 GWh/year;

d. Regarding the potential reductions in CO2equivalent emissions, the S1 scenario (landfill with energy recovery) is the lowest with a value of 1093.2 kt, which corresponds to a carbon credit of US$ 12,025,343 for each.

References

[1] Aguilar-Virgen, Q., Taboada-González, P., & Ojeda-Benítez, S. (2014). Analysis of the feasibility of the recovery of landfill gas: a case study of Mexico. *Journal of Cleaner Production*, *79*, 53-60.

[2] Gunamantha, M. (2012). Life cycle assessment of municipal solid waste treatment to energy options: Case study of KARTAMANTUL region, Yogyakarta. *Renewable energy*, *41*, 277-284.

[3] Arafat, H. A., Jijakli, K., 2013. Modeling and comparative assessment of municipal solid waste gasification for energy production. Waste Manage. 33, 1704-1713.

[4] Mahmoudkhani, R., Valizadeh, B., Khastoo, H., 2014. Greenhouse Gases Life Cycle Assessment (GHGLCA) as a decision support tool for municipal solid waste management in Iran. J. Environ. Health Sci. Eng. 12, 71.

[5] Thanh, N. P., Matsui, Y., 2013. Assessment of potential impacts of municipal solid waste treatment alternatives by using life cycle approach: a case study in Vietnam. Environ. Monit. Assess. 185, 7993-8004.

[6] Bernstad, A., la, C. J. J., 2012. Review of comparative LCAs of food waste management systems e current status and potential improvements. Waste Manage 32, 2439-2455.

[7] Ho WS, Hashim H, Lim JS, Lee CT, Sam KC, Tan ST. Waste management pinch analysis (WAMPA): application of pinch analysis for greenhouse gas (GHG) emission reduction in municipal solid waste management. Appl Energy 2017; 185: 1481–9.

[8] Ayodele, T. R., Ogunjuyigbe, A. S. O., & Alao, M. A. (2017). Life cycle assessment of waste-to-energy (WtE) technologies for electricity generation using municipal solid waste in Nigeria. Applied energy, 201, 200-218.

[9] Kra Essi Kouadio Francis, Kouakou Adjoumani Rodrigue, Kouadio Marc Cyril, & Akichi Agboue. (2020). Landfill's solide waste management: life cycle assessment and gas potential generation of Akouedo in Abidjan. *Australian Journal of Basic and Applied sciences*, *14* (07), 14-22.

[10] République de Côte d'Ivoire, Institut National de la Statistique (INS) 2014. Recensement général de la population et de l'habitat (RGPH) 2014: Donnés socio-démographiques et économiques des localités: Résultats provisoires par par localité, Région des lagunes.

[11] TERRABO-Ingénieur Conseil. (2010). Etude de caractérisation des déchets urbains du District d'Abidjan. Rapport final/MESU/DGVCV. 107.

[12] Cyril, K. M., Essi, K., Akichi, A., & Albert, T (2018). Characterization of the Parameters and Estimation of Potential Biogas of A Landfill in Tropical Area: Case Study of the Principal Landfill of Abidjan Akouedo Landfill. Research & Reviews: Journal of Ecology and Environmental Sciences, 6(1), 43-49.

[13] Liu, Y., Ni, Z., Kong, X., & Liu, J. (2017). Greenhouse gas emissions from municipal solid waste with a high organic fraction under different management scenarios. Journal of Cleaner Production, 147, 451-457.

[14] Zaman, A. U. (2010). Comparative study of municipal solid waste treatment technologies using life cycle assessment method. International Journal of Environmental Science & Technology, 7(2), 225-234.

[15] Tan, R. B., & Khoo, H. H. (2006). Impact assessment of waste management options in Singapore. Journal of the Air & Waste Management Association, 56(3), 244-254.

[16] Vergara, S. E., Damgaard, A., & Horvath, A. (2011). Boundaries matter: Greenhouse gas emission reductions from alternative waste treatment strategies for California's municipal solid waste. Resources, Conservation and Recycling, 57, 87-97.

[17] US EPA (2016) Inventory of US greenhouse gas emissions and sinks: 1990–2014, EPA 430-R-16- 002, Washington.

[18] Assamoi, B., & Lawryshyn, Y. (2012). The environmental comparison of landfilling vs. incineration of MSW accounting for waste diversion. Waste management, 32(5), 1019-1030.

[19] Hamid RA. 2011. Landfill gas to energy: incentives & benefits. Orlando, Florida:University of Central Florida.

[20] EPA U. Available and emerging technologies for reducing green house gas from municipal solid waste landfills US EPA; 2011.

[21] Bove, R., & Lunghi, P. (2006). Electric power generation from landfill gas using traditional and innovative technologies. Energy conversion and management, 47(11-12), 1391-1401.

[22] Arena, U. (2012). Process and technological aspects of municipal solid waste gasification. A review. Waste management, 32(4), 625-639.

[23] Thompson S, Sawyer J, Bonam R, Valdivia JE (2009) Building a better methane generation model: validating models with methane recovery rates from 35 Canadian landfills. Waste Manage (Oxford) 29:2085–2091.

[24] IPCC, 2002. CH4 emissions from solid waste disposal. In: Background Papers- IPCC Expert Meetings on Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. Institute for Global Environmental Strategies (IGES), Japan, pp. 419-439.

[25] Aguilar-Virgen, Q., Taboada-González, P., Ojeda-Benítez, S., & Cruz-Sotelo, S. (2014). Power generation with biogas from municipal solid waste: Prediction of gas generation with in situ parameters. Renewable and Sustainable Energy Reviews, 30, 412-419.

[26] Parikh, J., Channiwala, S. A., & Ghosal, G. K. (2005). A correlation for calculating HHV from proximate analysis of solid fuels. Fuel, 84(5), 487-494.

[27] Gómez, A., Zubizarreta, J., Rodrigues, M., Dopazo, C., & Fueyo, N. (2010). Potentialand cost of electricity generation from human and animal waste in Spain. Renewable Energy, 35(2), 498-505.

[28] Salami L, Susu AA, Patinvoh RJO, Okewole A. 2011. Characterisation of solid wastes: a case study of Lagos state. Int J Appl Sci Technol; 1:47–52.

[29] Ryu C. Potential of municipal solid waste for renewable energy production and reduction of greenhouse gas emissions in South Korea. J Air Waste Manage Assoc 2010; 60: 176–83.

[30] IPCC. 2006 IPCC guidelines for national greenhouse gas inventories. IPCC fourth assessment report. Geneva, Switzerland: IPCC; 2006.

[31] Mohareb EA, MacLean HL, Kennedy CA. Greenhouse gas emissions from waste management—assessment of quantification methods. J Air Waste Manag Assoc 2011; 61: 480–93.

[32] IPCC. 2006. Waste. In: Pipatti R, editor. Biological treatment of solid waste. Guidelines for national greenhouse gas inventories, vol. 5 – Waste: Geneva, Switzerland: Intergovernmental Panel on Climate Change.

[33] Zhang, D. Q., Tan, S. K., & Gersberg, R. M. (2010). Municipal solid waste management in China: status, problems and challenges. Journal of environmental management, 91(8), 1623-1633.

[34] Zairi, M., Aydi, A., & Dhia, H. B. (2014). Leachate generation and biogas energy recovery in the Jebel Chakir municipal solid waste landfill, Tunisia. Journal of Material Cycles and Waste Management, 16(1), 141-150.

[35] Kumar, K. N., & Goel, S. (2009). Characterization of municipal solid waste (MSW) and a proposed management plan for Kharagpur, West Bengal, India. Resources, Conservation and Recycling, 53(3), 166-174.

[36] Yang, N., Zhang, H., Shao, L., Lü, F., He, P., 2013. Greenhouse gas emissions during MSW landfilling in China: influence of waste characteristics and LFG treatment measures. J. Environ. Manage 129, 510-521.

[37] Tsunatu, D. Y., Tickson, T. S., Sam, K. D., & Namo, J. M. (2015). Municipal solid waste as alternative source of energy generation: a case study of Jalingo Metropolis–Taraba State. International Journal of Engineering and Technology, 5(3), 185-193.

[38] Chaya, W., & Gheewala, S. H. (2007). Life cycle assessment of MSW-to-energy schemes in Thailand. Journal of Cleaner Production, 15(15), 1463-1468.

[39] Guermoud, N., Ouadjnia, F., Abdelmalek, F., & Taleb, F. (2009). Municipal solid waste in Mostaganem city (Western Algeria). Waste Management, 29(2), 896-902.

[40] Chen, Z., Gong, H., Jiang, R., Jiang, Q., & Wu, W. (2010). Overview on LFG projects in China. Waste management, 30(6), 1006-1010.

[41] Yousuf TB, Rahman M (2007) Monitoring quantity and characteristics of municipal solid waste in Dhaka City. Environ Monit Assess 135: 3–11.

[42] Sharholy M, Ahmad K, Mahmood G, Trivedi RC (2008) Municipal solid waste anagement in Indian cities. Waste Manage (Oxford) 28: 459–467.

[43] Abu-Qudais M, Abu-Qdais HA (2000) Energy content of municipal solid waste in Jordan and its potential utilization. Energy Convers Manage 41: 983–991.

[44] JF, N., ROGAUME, T., KOULIDIATI, J., & SEGDA, B. (2013). Contribution a l'évaluation du pouvoir calorifique inferieur du dechet modele des pays en developpement: cas de la fraction combustible des ordures ménagères (OM) du Burkina Faso. Sciences des Structures et de la matière, 1(1).

[45] Tan, S., Hashim, H., Lee, C., Taib, M. R., & Yan, J. (2014). Economical and environmental impact of waste-to-energy (WTE) alternatives for waste incineration, landfill and anaerobic digestion. Energy procedia, 61, 704-708.

[46] Pathak, H., Jain, N., Bhatia, A., Mohanty, S., Gupta, N., 2009. Global warming mitigation potential of biogas plants in India. Environ. Monit. Assess. 157, 407-418.