Bibliographical review on assessment methodologies to evaluate the electrical energy recovered from biomass conversion technologies

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Abstract. Biomass conversion technologies offer clean, sustainable, and renewable electrical energy from biogas that is leaking into landfills. This energy based organic largely replaces fossil fuels in industrial and manufacturing activities, without forgetting its contribution to the reduction of greenhouse gases. In this work, we have indicated the methodology to evaluate the energy recovery of biomass that any operator in this field of activity can use to anticipate, control, and improve the productivity and the functioning of the landfill controlled site. The interest of the use of a combinatorial methodology between the three experimental, theoretical and numerical models offers the advantages for anticipate all the problems, using the most common solutions such as installing all the possible equipment for the permanent verification of the site impermeability by detecting the oxygen content, of the degradation, of the mechanical system of the site by measuring the hydrogen sulphide concentration, of breakdowns detections, and loss of methane. In addition, the artificial intelligence applications can be implemented to predict of biomass feedstock properties, process optimization and design for biomass conversion, optimal utilization of bioenergy, and supply chain design and planning respectively using four categories.

1 Introduction

At present, there are strong calls and significant challenges for the development of renewable energy systems, such as electrical energy produced from biomass conversion technologies from household waste [1]. This energy is produced from electric generators located in technical waste landfill sites, where the combustible gas being biogas defined as the primary product of biomass composed mainly of methane (CH_4) and carbon dioxide (CO_2) [2]. Given its high methane content, biogas must be effectively captured from landfills in order to avoid the risk of ignition and explosion [3]. And knowing that CH_4 being 35 times more influential on the greenhouse effect than CO_2, capturing it, collecting it, burning it or using it for the production of energy, being essential for the reduction of the

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greenhouse effect, its recovery (in heat, electrical energy, etc.) constitutes a contribution to sustainable development [4].

Globally, energy issued from the biogas is ranked fourth after coal, oil and natural gas, because this combustible gas is composed mainly of methane (CH_4) and carbon dioxide (CO_2) [5]. The use of biomass energy will represent 10 to 20% of the structure of global energy consumption by 2050 [6]. And according to the analysis carried out by the "Global methane initiative" in the partner countries where the consumption economies are on the rise and the population growth is high, such as the United States, China and Brazil, it is found that the elimination rate waste and methane production from model sanitary landfills are also on the rise [7]. The productivity of methane and electrical energy from these landfills has been the subject of numerous studies, articles and works to describe the operating conditions and the calculation processes for obtaining them [6-7]. In particular, we find Puente Hills Waste Sanitary Landfill Site (in California, United States) [8], São João Waste Sanitary Landfill Site (in São Paulo, Brazil) [9], and Gao'antun Waste Sanitary Landfill Site (Chaoyang District in Beijin, China) [10]. The studies carried out on these sites have predicted equivalent electrical energy and methane production about; 50 MW-54000 m3/h for the Puente Hills Waste Sanitary Landfill Site [11], 22.4 MW-11555 m3/h for the São João Waste Sanitary Landfill Site [7-9], and 2.5 MW-328 m3/h respectively for the Gao'antun Waste Sanitary Landfill Site [7, 10, 12].

However, and despite the great biomass potential available and a growing demand for electrical energy, the energy recovery of biomass is very little developed on a global scale, being limited to 12% of gross final energy consumption according to statistics from the World Bioenergy Association [13]. In addition, this field has many problems, both in calculation and prediction methods and in evaluation methods [14]. Some authors only use the experimental method to assess the profitability of the landfill site [15, 16, 17]. Others use theoretical models for the prediction of the productivity of methane and electrical energy by analogy [18, 19, 20]. Recently, explorers of this activity only use numerical models to exploit the quantities of all the components of biogas produced by controlled landfills, and to predict the electrical energy for the recovery of their sites [21, 22, 23].

The objective of our work is to describe a methodology that will combine the three models: theoretical, numerical and experimental at the same time, using the most recent calculation methods and the most confirmed in the scientific literature. Those, in order to evaluate the productivity of the landfill site in methane and electrical energy that any operator in this field of activity can obtain to control, anticipate productivity and act correctly on the operating parameters of landfills, in addition to the applications used the artificial intelligence.

2 Materials and methods

2.1 Prediction models

2.1.1 Theoretical Model

This model was based primarily on the reaction of biological degradation of complex polymer of organic matter or biomass also called methanation [24]. It has been the subject of numerous studies, articles and works to describe the general biochemical process, and to derive a simplistic macroscopic theoretical equation describing the conversion of any generic organic compound including nitrogen and sulfur ($C_aH_bO_cN_dS_e$) into methane (CH_4), carbon dioxide (CO_2), ammonia (NH_3) and hydrogen sulfide (H_2S) using reaction (1) [25].

$$C_aH_bO_cN_dS_e+(a-b/4-c/2+3d/4+e/2)H_2O \rightarrow (a/2+b/8-c/4-3d/8-e/4)CH_4+ (a/2-b/8+c/4+3d/8+e/4)CO_2+dNH_3+eH_2S \quad (1)$$

The simplified form of reaction (1) is the reaction (2), which we note A and B reactants, C, D, E and F products for development of the equation formula [19].

$$A+C_1B \rightarrow C_2C+C_3D+C_4E+C_5F \quad (2)$$

The hypotheses of this model assume that the elements of carbon, hydrogen, oxygen, nitrogen and sulfur are the only components of the raw material [18-19]. And the method for determining chemical reaction constants C_1, C_2, C_3, C_4 and C_5 from the reaction (2) is the ultimate analysis developed with the estimating of chemical formula of the raw material [26]. This says that the constant of each element is equal to the ultimate mass based on the ultimate analysis of determining the different chemical elements present in a particular compound, divided by the molar mass of the element, hence the presentation of the ratios of mass of C, H, O, N, and S (in grams) which are then defined as variables [18-19].The notation of the molar masses of carbon (mm_C), hydrogen (mm_H), oxygen (mm_O), nitrogen (mm_N) and sulfur (mm_S) are given as follows in the table 1 [26].

As a result, and applying the elemental composition of the biomass used by the Boyle formulas linked to the aforementioned model, the theoretical biochemical potential of methane TBMP (in ml CH4 gVS-1) is calculated by formula (3), and developed with used the mathematics formulas as explained in table 1 [18, 19, 20].

$$TBMP = [22.4*(a/2+b/8-c/4-3d/8-e/4)]/ [(12,017*a)+(1,0079*b)+(15,999*c)+(14,0067*d)+(32,065*e)] \quad (3)$$

Table 1. Mathematics formulas for developed of the TBMP equation (3)

Items	Formula developed	Number	Reference
Constants C_1 for the reaction (2)	$C_1=a-(b/4)-(c/2)+(3d/4)+(e/2)$	(4)	[18, 19, 20, 24, 25, 26]
Constants C_2 for the reaction (2)	$C_2=(a/2)+(b/8)-(c/4)-(3d/8)-(e/4)$	(5)	[18, 19, 20, 24, 25, 26]
Constants C_3 for the reaction (2)	$C_3=(a/2)-(b/8)+(c/4)+(3d/8)+(e/4)$	(6)	[18, 19, 20, 24, 25, 26]
Constants C_4 for the reaction (2)	$C_4=d$	(7)	[18, 19, 20, 24, 25, 26]
Constants C_5 for the reaction (2)	$C_5=e$	(8)	[18, 19, 20, 24, 25, 26]
Constant a for the formulas (4,5 and 6)	$a=a_{\mathrm{ultimass}}/mm_C= a_{\mathrm{ultimass}} /12,0107$	(9)	[18, 19, 24]
Constant b for the formulas (4,5 and 6)	$b=b_{\mathrm{ultimass}}/mm_H= b_{\mathrm{ultimass}} /(1,0079)$	(10)	[18, 19, 24]
Constant c for the formulas (4,5 and 6)	$c=c_{\mathrm{ultimass}}/mm_O=c_{\mathrm{ultimass}}/(15,999)$	(11)	[18, 19, 24]
Constant d for the formulas (4,5,6 and 7)	$d=d_{\mathrm{ultimass}}/mm_N=d_{\mathrm{ultimass}}/(14,0067)$	(12)	[18, 19, 24]
Constant e for the formulas (4,5,6 and 8)	$e=e_{\mathrm{ultimass}}/mm_S=e_{\mathrm{ultimass}}/(32,065)$	(13)	[18, 19, 24]
Molar mass in g/mol of a compound or reactant A with the	$mm_A=(a*mm_C)+(b*mm_H)+(c*mm_O)$ $+(d*mm_N)+(e*mm_S)$ $=12,017*a+1,0079*b+15,999*c+1$	(14)	[18, 19, 24, 25, 26, 27]

chemical formula $C_aH_bO_cN_dS_e$	$4,0067*d+32,065*e$		
Molar mass in g/mol of the reactant B	$mm_B=(2*mm_H)+(1*mm_O)=2*1,0079+1*15,999=18,0158$ g/mol	(15)	[18, 19, 24, 25, 26, 27]
Molar mass in g/mol of the reactant C	$mm_C=mm_C+(4*mm_H)=12,017+4*1,0079$ $=16,04$ g/mol	(16)	[18, 19, 24, 25, 26, 27]
Molar mass in g/mol of the product D	$mm_D=(1*mm_C)+2*mm_O$ $=1*12,017+2*15,999=44,02$ g/mol	(17)	[18, 19, 24, 25, 26, 27]
Molar mass in g/mol of the product E	$mm_E=(3*mm_H)+(1*mm_N)=3*1,0079+1*14,0067=17,03$ g/mol	(18)	[18, 19, 24, 25, 26, 27]
Molar mass in g/mol of the product F	$mm_F=(2*mm_H)+(1*mm_S)$ $=2*1,0079+1*32,065=34,08$ g/mol	(19)	[18, 19, 24, 25, 26, 27]

Before proceeding to the calculation developed by the aforementioned theoretical model, the assumptions concerning the landfill site to be studied must be confirmed [18-19].

- Complete digestion or ideal bacterial conditions;
- Incoming waste only consists of C, H, O, N and S;
- Reaction products include only CH_4, CO_2, NH_3 and H_2S;
- No ash accumulation;
- Constant temperature and perfect mixing.

Therefore, the creation of a model that takes into account all the different complicated parameters such as; incomplete digestion, presence of toxins, insufficient mixing, establishment of microbial populations, complexity of lignin structure, effects (pH, temperature and redox) requires the use of a limiting factor (f=80%) in order to adjust the gas produced under unrealistic conditions to the gas produced under real conditions [19, 26, 27].

To calculate the theoretical electrical energy that a landfill site can produce from the value of TBMP, we proceed by analogy using the values from the ultimate analysis of the scientific literature, this is indicated in the formula (19) [28-29].

$$E_{Th}=M_{AW}*TBMP*f*C_{CH4} \qquad (19)$$

With:

ETh : Annual theoretical electrical energy in kWh/year;
MAW : Tonnage of waste in kg/year;
TBMP : Theoretical biochemical potential of methane in ml CH_4 gVS-1;
C_{CH4} : Lower calorific value of methane in kWh/m^3;
f : Limiting factor.

2.1.2 Numerical Model

Since the end of the last century, many scientists have devoted to the numerical modeling of the reaction process of anaerobic digestion [30]. After repeated practices and comparisons by many scholars, different models for estimating landfill gas emissions (LFG landfills generates landfill gas) have been developed, and each incorporates new factors and features to introduce distinct approaches or achieve more accurate results [21-22]. Landfill gas generation can be modeled as a zero-, first-, or second-order equation [23]. However, data obtained from laboratory and field observations suggest that the overall decomposition process of municipal solid waste (MSW) in landfills models first-order kinetics [21, 22, 23]. Thus, most studies have shown that zero-order kinetics is not accurate enough to represent methane generation [21-22]. Also, second-order models involve a more complicated procedure that is not justified by increased accuracy [21, 22, 23].

Among the models of the first order; we find: LandGEM (Landfill Gas Emissions Model) and the IPCC model which are the most applied models to estimate the production of methane [21]. They provide default values of input parameters for sites and areas lacking specific input data [22]. In addition LandGEM, the model developed by the United States Environmental Protection Agency (USEPA: Environmental Protection Agency of U.S) is the most widely used, efficient and accurate model compared to other models [30-31].

This model can be used for the design and installation of an energy recovery system in addition to the prediction of the production of biogas such as (CO_2, CH_4, traces of NMOC (non-methane organic compounds) and other pollutants), and like most FOD first-order decay models, it is based on two critical factors ('Lo' and 'k') as mentioned in equation (20) [23]:

$$Q_{CH4}=\sum_{(i=1)}^{n}\sum_{(j=0.1)}^{1}[kL_{O}*(M_{i}/10)*e^{(-kt_{ij})}] \qquad (20)$$

Where, Q_{CH4} denotes annual methane generation in the year of the calculation (m3/year), i is 1-year time increment, Mi shows the mass of waste accepted in the ith year (Mg), n indicates (year of the calculation) - (initial year of waste acceptance), tij is the age of the jth section of waste mass Mi accepted in the ith year (decimal years, e.g., 3.2 years), j indicates 0.1-year time increment, k shows the first order methane generation rate (year-1) , Lo denotes potential methane generation capacity (m3/Mg) [30-31].

For the estimation of the electricity production from the quantity of methane predicted by the LANDGEM model, we use the formula (21) [28].

$$E_{Nm}=P_{t} * Q_{CH4} * \eta_{e} \qquad (21)$$

With :

E_{Nm}: Annual numerical production of electrical energy in (kWh/year);

P_t: Lower calorific value of methane from landfill 9,94kWh/m3;

Q_{CH4}: Annual methane generation in the year of the calculation (m3/year);

η_e : Efficiency of the facility producing electricity from methane from the landfill, the efficiency of these systems generally varies between 30% and 40%, Depending on the properties of the engine or gas turbine installed.

2.2 Experimental method

This method begins with the location of the study of the landfill site, which gathers its geographical position, and all these constructions including the bioelectric station, the access roads, the lockers and circuits for the collection and treatment of leachate, the channels for the collection and treatment of biogas, the circuit for the collection and evacuation of rainwater, the biogas withdrawal stations, the pretreatment and recovery units, and the arrangements of the wellheads [15, 16, 17].

To evaluate the biogas produced and calculate the quantity produced in methane, we proceed first by taking measurements from independent butterfly and ball valves installed at the outlet of wellheads in landfills [32]. At the same time, daily measurements of the tonnages of the organic load at the inlet of the anaerobic digester were taken; it is preferable to hold a measurement period spread over the whole year to cover all the seasons of change in the outdoor climate [33].

The measurements of the composition of biogas, is carried out using the biogas analyzer [34]. This apparatus must have the characteristics of resolution, precision, measurement range, and speed response time, the most powerful possible to realize the analyses of the composition of biogas in O_2, CH_4, CO_2, and H_2S [16].

The electrical energy is calculated using the average concentration of methane from the biogas analyzer, the average flow of biogas produced by the channels buried under the waste and displayed by the flow meter at the outlet of the main collector, and the cumulative tonnage values in the year of experimental study as mentioned in the formula (22) [15, 16, 35].

$$E_{Ex}=C_p * Q_{biogaz} * C_{methane} \tag{22}$$

With:

E_{Ex}: Annual experimental production of electrical energy in kWh/year;
Cp: Lower calorific value of methane from landfill in kWh/m3;
Q_{biogaz}: Annual Average biogas flow obtained by the flow meter in m3/year;
$C_{methane}$: Annual Average concentration of methane from the biogas analyzer in %.

2.3 Artificial intelligence applications

Recently, the Artificial Intelligence (AI) has received increasing interest. AI refers to machines' ability to perform activities that mimic human intelligence and could be implemented through different techniques in computer science, like machine learning, heuristic algorithms, and fuzzy logic [36]. Many applications have been demonstrated in different domains, such as chemical engineering, intelligent manufacturing, and building energy conservation compared with AI applications to bioenergy systems are limited [37]. However, previous studies indicated the tremendous potential of AI in addressing barriers in bioenergy development [36-37].

According to the latest publications in the scientific literature, we can see that the applications of artificial intelligence in the field of bioenergy are classified into four categories [37]. The latter take into consideration the complexity of bioenergy systems which is presumed in network that involves crop cultivation, harvest, feedstock pre-treatment, energy conversion, transportation, and industrial or household usage, in addition to several aspects, such as feedstock production, process optimisation, use phase and post-treatment, and supply chain with impact assessment [36].

The representation as followed in the figure 1 explains the four categories of artificial intelligence applications in the field of bioenergy, the total number of corresponding publications, and the countries that best develop these applications [36-37].

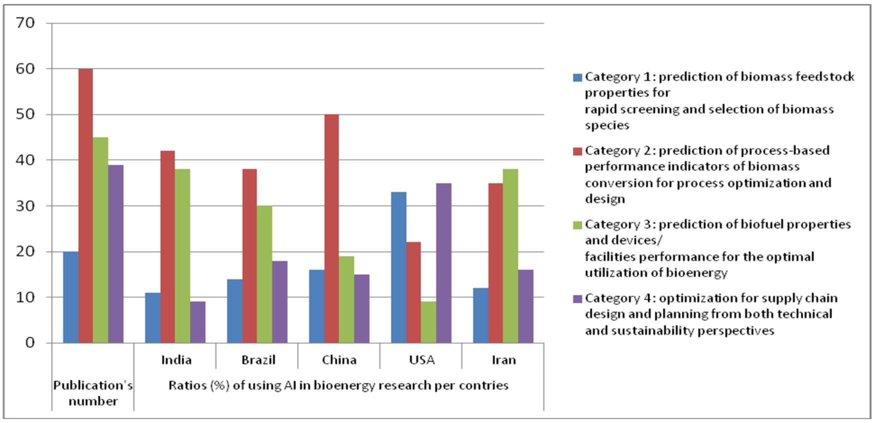

Fig. 1. Representation of the four categories of artificial intelligence applications in the field of bioenergy

3 Results and discussions

Using the combinatorial methodology as indicated in the figure 2 between the three models experimental, theoretical and numerical, and whose calculation steps have been detailed in the previous paragraphs. Any operator in this field of activity can achieve a total assessment of quantity and quality of methane and energy equivalent. On site this can be integrated by installing all the possible equipment for the permanent verification.

Using the biogas analyzer to detect the concentrations of CH_4, CO_2, O_2, and H_2S, allows the operator to control the state of the technical landfill site and provide possible solutions for better production.

The concentration margins to be respected for the biogas components and the results from the scientific literature are detailed as follows.

To better understand the causes of the fall in the production of CH4 in the areas of the landfill surrounding the wellheads, we used the results measurement of the percentage of oxygen sampled in parallel with those of methane by the same wellheads. Because the low methane production may be due to the presence of conditions that are not favourable to anaerobic digestion because the methanation is a reaction that takes place in the absence of oxygen [38]. And the methanogenic bacteria responsible for producing methane are strictly anaerobic, which is why methanogenic bacteria will die in the presence of oxygen [39].The normally range production existing in the scientific literature, which is between 50% and 70% for CH_4 and between 0,2 and 0,4 for O_2 [38].

CO_2 has a direct relation with the organic compounds reacted by anaerobic digestion, which it forms part as products of said reaction (1). In general, the CO_2 levels contained in the biogas are between 30% and 47% [40]. While CO_2 does not contribute at any time to the degradation of the mechanical system of the site, H_2S causes corrosion and mechanical wear increasing maintenance costs drastically, thus posing occupational health and safety problems from its colorless nature, flammable and extremely dangerous [41]. In general, the H2S content in biogas from the anaerobic digestion of municipal organic waste is 500-4000 ppm, however a large value in H2S confirms the existence of organic sulfur compounds in the in buried waste [42].

The stability and progress of landfill fermentation are key indicators of the degradation of fermentable organic matter in landfill, whose CH_4/CO_2 content ratio must be less than or equal to two [40, 41, 42]. Adopting the most common and fastest solutions for abnormal values detected by the biogas analyzer will improve the operating parameters of the landfill site. And also have better productivity in terms of methane and electrical energy.

According to the figure 1, the artificial intelligence applications in the field of bioenergy can be used to predict of biomass feedstock properties for rapid screening and selection of biomass species by Category 1, for prediction of process-based performance indicators of biomass conversion for process optimization and design by Category 2, for prediction of biofuel properties and devices facilities performance for the optimal utilization of bioenergy by Category 3, for optimization for supply chain design and planning from both technical and sustainability perspectives by Category 4.

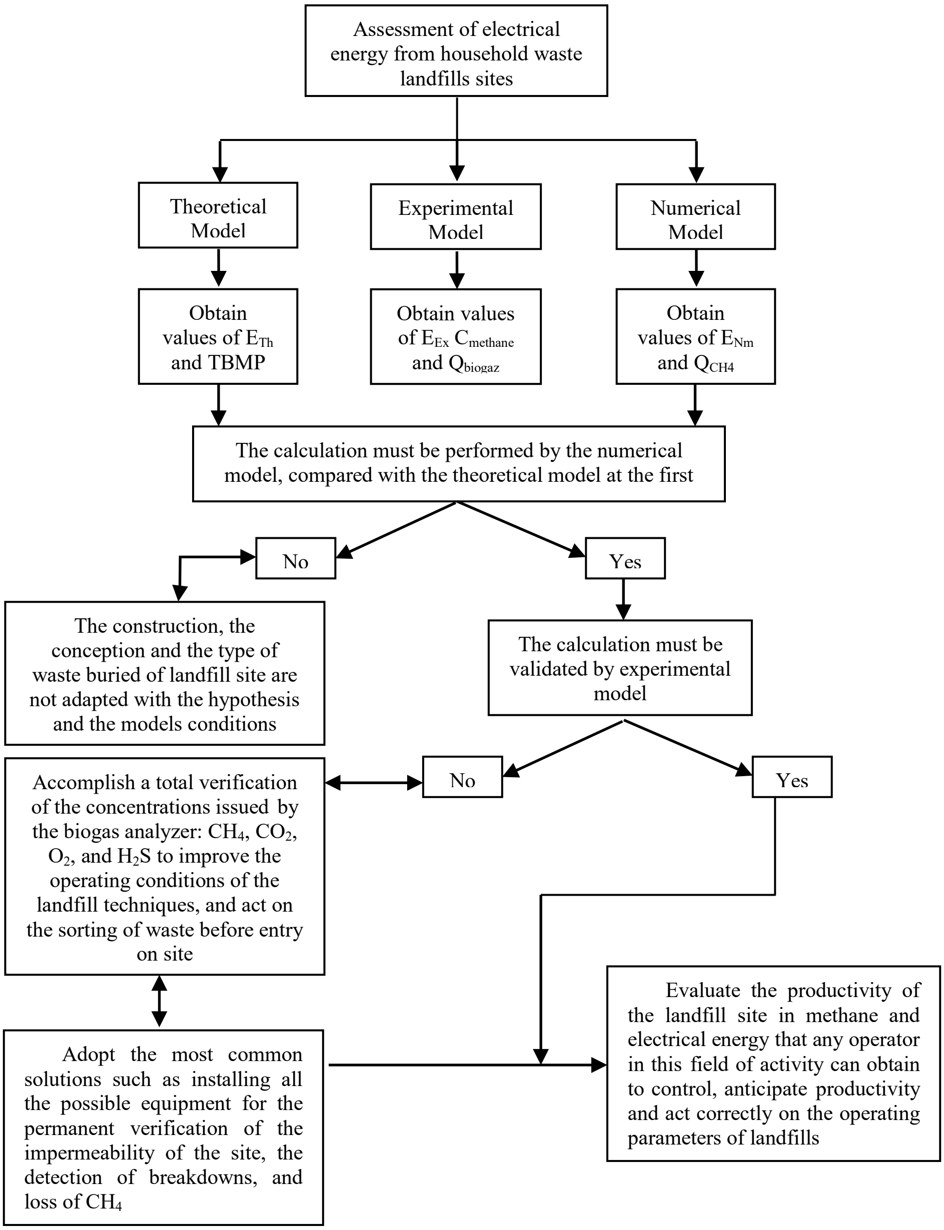

Fig. 2. Decision of assessment methodology to evaluate the electrical energy recovered from biomass conversion technologies (case study of household waste landfills sites)

4 Conclusion and perspectives

In this work, we have demonstrated the potential of the use of a combinatorial methodology between the three experimental, theoretical and numerical models, where any operator in this domain can use to anticipate, control, and improve the productivity and the functioning of the landfill site.

The concentration margins of the biogas components (CH_4, CO_2, O_2, and H_2S) indicated by the scientific literature must to be respected on the site, their values are essential to know the sources of all problems acting on the experimental calculation. And consequently adopt the possible and effective solutions to respect the conditions of the proper functioning of the landfill site, and consequently have very good results in terms of methane and electrical energy.

The artificial intelligence applications using the four categories can be implemented to predict of biomass feedstock properties, process optimization and design for biomass conversion, optimal utilization of bioenergy, and supply chain design and planning respectively. The algorithm adopted and all the calculation details are the studies that well be improved in the future researches.

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