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Energy Recovery Potential of Livestock Waste with Thermal and Biological Technologies: Analysis on Cattle, Sheep, Goat and Chicken Manure

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ABSTRACT

This study aims to establish the scientific link between the livestock wastes and energy recovery processes to implement the most appropriate technology at the highest economic benefit. The evaluation was based on the recovery of the potential energy of the mixture of four livestock wastes (cattle, sheep, goat, egg chicken) by four different energy recovery processes. Incineration, gasification, pyrolysis at 550°C and 750°C were applied as thermal processes together with the anaerobic digestion as biochemical process. The recovery performance of each process was evaluated within a defined design algorithm considering all significant parameters in seven geographical regions and in Turkey as a whole. Incineration seems to be the most efficient energy recovery process with 0.43 MWe/t for Turkey. Gasification took the second place in the energy recovery ranking with 0.34 MWe/t, 21% less than incineration. Pyrolysis expressed an energy recovery rate of 0.15 MWe/t at 550°C and a twice higher rate at 750°C, at a level close to gasification. Anaerobic digestion exerted a recovery potential of 0.21 MWe/t for the livestock waste considered. Energy recovery from livestock waste not only contributes to energy production, but also provides compliance with the concept of reducing emissions and sustainable environment.

Keywords: Energy Recovery, Livestock Waste, Incineration, Gasification, Pyrolysis, Anaerobic Digestion
JEL Classifications: Q29, Q42, Q560

1. INTRODUCTION

The necessity for the minimization of waste and using waste as a resource within the concept of sustainable environment and Green Deal lead to the careful feasibility of the association of waste and energy recovery technologies. The basic principle of these concepts is to apply clean technologies to avoid waste generation, if possible or waste reduction and reuse and recycle in cases where waste generation is inevitable. Especially in industries with high amount of organic waste the energy recovery from waste becomes vital instead of disposal of the waste (Akyurek, 2019a; Hasan et al., 2021; Hadin et al., 2017).

Livestock processing is a typical agro-industry generating a strong wastewater in terms of organics, solids and nitrogen content and significant amount of solid waste. Basic approaches in the past have often followed the mixing of these two waste streams resulting in various treatment and disposal problems. The new strategies in the sustainable environment management direct to a better in-depth look at the processes leading to minimization of the waste, reuse and/or recovery to the highest extent possible (Germirli Babuna et al., 2006; Wan et al., 2019) to reduce their environmental impacts. The solid waste, also called as manure, with its high organic content, unlike the previous applications as mostly disposed to sites, is nowadays assessed as one of the main renewable energy sources within the sustainable environment concept. Several technologies are evaluated to find out the most suitable energy recovery technologies. Energy recovery from manure is a kind of clean bioenergy with low carbon footprint and helps for limiting the agricultural GHG emission contributions to global climate change (Akyurek, 2019b).

Cattle, sheep, goat and poultry breeding activities create a high amount of solid organic waste with high energy potential. The lower calorific value of cattle manure differs between 3,623 and 4,613 kcal/kg, sheep manure around 3,121 kcal/kg, and egg chicken manure between 3,046 and 4,101 kcal/kg (Tsai and Liu, 2019; Yin et al., 2010; Touray et al., 2014; Tanczuk et al., 2019a; Tanczuk et al., 2019b; Sun et al., 2016).

In this framework, the objective of the study was to determine the recoverable amount of total energy of livestock waste with different energy recovery processes. This goal was accomplished by means of incineration, gasification and pyrolysis as thermal processes together with anaerobic digestion as a biological process to figure out the most feasible recovery rate within a methodology. The methodology outlined specific algorithms for four different processes to convert the waste to useful energy by recognizing all significant parameters defining a unified basis. The major livestock activities in Turkey are considered as an inventory for energy recovery management. The scope of the study was limited to only present how the energy recovery potentials differ when different technologies are applied. Other environmental benefits and aspects related with processes are not addressed in the scope of this study.

2. REVIEW OF LITERATURE

The majority of livestock activities in Turkey were mainly based on cattle, sheep, goat and chicken breeding. The most relevant data related to the amount of manure were given in Biomass Potential Atlas prepared by General Directorate of Renewable Energy in Turkey. The total amount of raw livestock waste produced in 2018 was given as 154,872,561 t/year. The majority of the livestock waste in all geographic regions was cattle manure differing between 61% to 77% with a countrywide average 69% (107,442,350 t/year). Contrarily, the minority of the livestock waste was egg chicken manure with 4% (5,950,736 t/year) countrywide average on the total amount. The maximum amount of livestock waste was seen in Black Sea region with 25,001,890 t/year where the minimum amount was in Aegean region with 10,890,849 t/year.

The amount and distribution of the sources of livestock waste was quite important to define the physical, chemical and biochemical characteristics of mixed livestock waste to be fed into the energy recovery systems (Table 1).

The characterization of mixed livestock waste in each region and countrywide has been specified according to the physical, chemical, and biochemical properties of each waste type defined in the literature. The values used for this definition were given in Table 2-5, and the chosen value were also shown for each livestock waste.

As shown in Table 2, DM contents for cattle wastes varied in the range from 98 g/kg to 250 g/kg, for sheep wastes between 400 and 614 g/kg, for goat waste between 471 g/kg and 516 g/kg and for chicken waste between 276 g/kg and 291 g/kg according to the literature research. Similarly, VS contents in terms of their ratio in the solids mass vary between 67% and 82% for cattle waste, between 51% and 81% for sheep waste, between 79% and 89% for goat waste, and between 57% and 74% for chicken waste.

As shown in Table 3, ash content differed within a range of 1.9% and 7.2% for cattle waste, 11% for sheep waste, from 6% to 17.3% for goat waste and from 15.6% to 17.5% for chicken waste. The elementary analysis results for livestock wastes in different literature sources were shown in Table 4.

As given in Table 5, the lower calorific value for cattle manure fluctuated from 3,623 kcal/kg to 4,613 kcal/kg, 3,121 kcal/kg for goat manure, from 3,046 kcal/kg to 4,101 kcal/kg for egg chicken manure.

Finally, specific methane generation rates for cattle manure and egg chicken manures were given in Table 6. The ratio for cattle manure was found in a range of 215–250 LCH_4/kgVS and of 184–359 LCH_4/kgVS for egg chicken manure. No reliable information on specific methane generation rates was specified in the literature for sheep and goat manures. These rates were calculated by using the molecular formula determined in accordance with the elemental composition (presented in Table 4) as shown in the algorithm given in Appendix A1-A4.

3. METHODOLOGY AND DATA

3.1. Data

3.1.1. Physical, chemical and biochemical properties of mixed livestock waste

The majority of livestock waste consisted by cattle manure, and at the same time cattle manure had the highest calorific value (Table 5). However, the moisture content of cattle manure was quite high where the average dry matter content is 19% (Table 2). This created a serious dewatering load for thermal processes. To avoid and minimize this load, cattle manure was considered to mix with

Table 1: Amount of livestock waste across the geographic regions of Turkey and countrywide for 2018 (MENR, 2019)

Region	Cattle	Sheep	Goat	Egg Chicken	Total
	t/year	t/year	t/year	t/year	t/year
Marmara	17,067,180	3,447,732	1,066,604	508,823	22,090,340
Aegean	10,890,849	2,031,624	383,252	976,751	14,282,476
Black Sea	25,001,890	9,919,233	1,869,082	1,123,451	37,913,655
Mediterranean	15,150,232	3,461,099	788,235	629,898	20,029,464
CA	14,981,726	6,928,427	1,963,026	512,723	24,385,902
EA	15,605,447	5,496,500	828,930	963,742	22,894,618
SEA	8,745,026	2,642,791	652,939	1,235,348	13,276,105
Turkey	107,442,350	33,927,407	7,552,068	5,950,736	154,872,561

Table 2: Dry matter (DM) and volatile solid (VS) content of livestock wastes

Livestock Waste Source	#	DM Content, g/kg	VS Content,%DM	Reference
Cattle manure	1	250	67	(Iglinski et al., 2012)
	2	250	80	(Oniszk-Poplawska et al., 2014)
	3	114	82*	(Sutaryo et al., 2014)
	4	98	81*	(Moset et al., 2017)
	5	236	69*	(Yin et al., 2010)
	Choice	190	76	
Sheep manure	1	600	51	(Oniszk-Poplawska et al., 2014)
	2	500	81*	(Song et al., 2019)
	3	400	73	(Imeni et al., 2019)
	4	614	55	(Alvarez and Liden, 2009)
	Choice	529	65	
Goat manure	1	555	89	(Imeni et al., 2019)
	2	471	80	(Cho et al., 2017)
	3	516	79	(Cho et al., 2017)
	Choice	514	83	
Egg chicken manure	1	277	74*	(Borowski et al., 2014)
	2	276	69*	(Li et al., 2013)
	3	291	68*	(Tanczuk et al., 2019a)
	4	285	57	(Feng et al., 2018)
	5	-	68*	(Tanczuk et al., 2019b)
	Choice	282	67	

*Calculated over volatile solids content of total mass.

Table 3: Ash content of livestock wastes

Livestock Waste source	#	Ash Content, %	References
Cattle manure	1	1.9	(Moset et al., 2017)
	2	1.5	(Moset et al., 2017)
	3	7.2	(Yin et al., 2010)
	Choice	3.5	
Sheep manure	1	11.0	(Imeni et al., 2019)
	Choice	11.0	
Goat manure	1	6.0	(Imeni et al., 2019)
	2	16.7	(Erdogdu et al., 2019)
	3	17.3	(Touray et al., 2014)
	Choice	13.3	
Egg chicken manure	1	17.5	(Jung et al., 2019)
	2	15.6	(Tanczuk et al., 2019b)
	Choice	16.6	

The elementary analysis results for livestock wastes in different literature sources were shown in Table 4.

much drier sheep and goat waste (average of 52.9% and 51.4% solids, respectively) and poultry waste (28.2% solids content) are for this study (Table 2). When they are mixed, the DM ratio of mixed livestock waste becomes 27.9 ± 3.4% on average (Table 7) which is relatively higher than the cattle manure's DM content (19%).

The parameters for mixed livestock waste were calculated by using the amount of each livestock waste in each region given in Table 1 and the chosen values in Table 2-6 for each parameter. The dry matter contents, volatile solids contents, ash contents, elementary analysis results, lower calorific values, and specific methane generation rates of mixed livestock waste were given in Table 7 for each region of Turkey and countrywide as calculated by using the information given in Tables 1-6.

3.2. Methodology

The approach of the study for selected energy recovery technologies which were incineration, gasification, pyrolysis and anaerobic digestion relied on the analysis and modelling of the available data. The flow scheme of the approach was given in Figure 1.

The three thermal disposal technologies - incineration, gasification and pyrolysis - included a mixing of all different sourced manure and applying a dewatering step at the beginning which needed to provide the relevant feeding conditions for each system. The energy requirement for dewatering was supplied by the thermal energy generated. After dewatering, the first option was to feed the dewatered manure into the incineration system and recovered energy from the steam. The second option was to feed them into a gasifier and to recover energy by burning the syngas in a suitable engine. The third option was the recovery of energy by feeding it into a pyrolysis reactor to obtain a synthetic gas and burning it in a suitable engine. The last option was the mixing the livestock waste without applying dewatering followed by anaerobic digestion to obtain biogas and recover energy by burning the biogas in a suitable engine.

3.2.1. Incineration process

The simulation of energy recovery for incineration relied on four main steps: mass balance, heat balance, steam production and energy recovery from steam. The calculation steps were described in detail in the algorithm given in Appendix A1. All steps in the algorithm depended on the waste characteristics and the amounts represented by Moisture Content (MC%), Ash Content (AC%), Lower Heating Value (LHV) together with raw waste input (RW_I). Thermal dewatering up to 15% MC was applied to the feed since the MC% of mixed livestock waste was quite high in all cases.

3.2.1.1. Mass balance

Starting with the top left-hand side of the algorithm in Appendix A1; first, the amount of flammable portion of waste and total heat resource, then heating value of flammables were calculated. Empirical formulas were formed to estimate the dry gas and

Figure 1: Flow scheme for energy recovery from mixed livestock waste

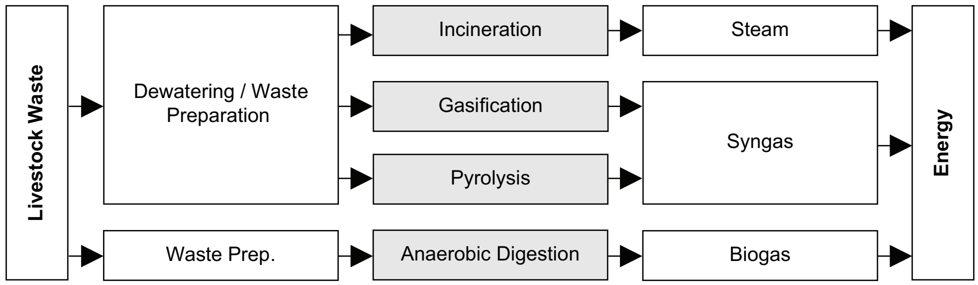


Table 4: Elemental analysis of livestock wastes

Livestock waste source	#	C, %	H, %	N, %	S, %	O, %	References
Cattle manure	1	43.7	5.5	0.8	0.0	50.0	(Tsai and Liu, 2019)
	2	44.3	5.9	0.8	0.0	48.9	(Tsai and Liu, 2019)
	3	35.4	4.7	2.4	-	57.5	(Yin et al., 2010)
	Choice	41.1	5.4	1.3	0.0	52.1	
Goat manure	1	42.1	5.6	1.5	0.9	39.9	(Erdogdu et al., 2019)
	2	40.1	5.9	2.0	-	41.2	(Touray et al., 2014)
	Choice	41.1	5.7	1.7	0.9	40.5	
Egg chicken manure	1	38.2	5.8	4.9	-	37.7	(Li et al., 2013)
	2	39.7	4.7	5.5	0.4	34.1	(Tanczuk et al., 2019)
	3	42.9	5.6	5.5	0.7	33.4	(Tanczuk et al., 2019)
	4	30.1	4.9	3.4	0.4	35.9	(Feng et al., 2018)
	5	39.7	4.7	5.5	0.4	34.1	(Tanczuk et al., 2019b)
	Choice	38.1	5.1	5.0	0.5	35.1	

Table 5: Lower heating values of livestock wastes

Livestock waste source	#	LHV, kcal/kg	References
Cattle manure	1	4,419	(Tsai and Liu, 2019)
	2	4,613	(Tsai and Liu, 2019)
	3	3,623	(Yin et al., 2010)
	Choice	4,218	
Goat manure	1	3,121	(Touray et al., 2014)
	Choice	3,121	
Egg chicken manure	1	3,046	(Tanczuk et al., 2019a)
	2	3,955	(Tanczuk et al., 2019a)
	3	3,046	(Tanczuk et al., 2019b)
	4	4,101	(Sun et al., 2016)
	Choice	3,537	

Unit conversion from MJ/kg to kcal/kg done for the values given in literature

Table 6: Specific methane generation rates of livestock wastes

Livestock waste source	#	Specific methane gen. rates, LCH_4/kgVS	References
Cattle manure	1	250	(Oniszk-Poplawska et al., 2014)
	2	305	(Moset et al., 2017)
	3	215	(Zarkadas et al., 2015)
	Choice	257	
Egg chicken manure	1	184	(Borowski et al., 2014)
	2	359	(Li et al., 2013)
	3	195	(Keskin et al., 2017)
	Choice	16.6	

moisture production by using the available charts. Then, excess air amount was calculated with the assumption of excess air ratio (A%), which was assumed as 100% as given by Tchobanoglous and Kreith (2002). At the initial step, the air required to burn the supplementary fuel ($A_{R,SF}$) was assessed as zero, estimated further in the following steps, if necessary. Next step was the calculation of the moisture entering into the incinerator with air feed, and at the final step the dry gas and the moisture leaving the incinerator. As previously explained, the dry gas ($D_{GP,SF}$) and the moisture ($M_{P,SF}$) contents came out during incineration of supplementary fuel (and respectively) were estimated as zero at the beginning, to be calculated in the next steps if needed.

3.2.1.2. Heat balance

Heat balance was correlated by considering the heat losses and heat corrections. There were three major heat losses and one heat correction in the incinerator (top right-hand side of the Algorithm in Appendix A1). First, the heat loss due to cooling air was calculated based on the amount of cooling air. 60 m³/min air was assumed to be served and the air temperature at the discharge point (T_{DP}) was supposed as 230°C (450°F) as recommended by Tchobanoglous and Kreith (2002). In the second step the assessment of the heat loss due to ash discharge was completed where the discharge temperature of ash (T_{AD}) was assumed as 315°C (600°F), the specific heat of ash ($H_{Sp.A}$) as 0.24 kcal/kg°C (0.24 BTU/lb°F) and the standard ambient temperature ($T_{Std.}$) as 16°C (60°F). The ratio of heat loss to radiation ($H_{LRR\%}$) was assumed as 1.5% to calculate the third heat loss caused by radiation. This ratio could be increased up to 3% depending on the decrease in the total heat resource. Finally, heat correction due to moisture content of air feed was estimated where the evaporation heat of air (H_E) was assumed as 540 kcal/kg (970 BTU/lb). The next step was the calculation of the total heat loss and the outlet. The outlet temperature based

Table 7: Characteristics of mixed livestock waste in geographic regions and in Turkey

Region	DM	VS	AC	C	H	N	S	O	LHV	Sp. CH_4 Gen. Rate
	%	% of DW*							kcal/kg	LCH_4/kg_{VS}
Marmara	26.03	74.11	5.46	41.04	5.39	1.46	0.76	51.01	4,136	252
Aegean	25.29	73.72	5.74	40.87	5.37	1.66	0.66	50.29	4,121	261
Black sea	29.70	72.94	6.35	41.00	5.39	1.51	0.72	50.60	4,109	260
Mediterranean	26.39	73.80	5.61	41.00	5.38	1.51	0.73	50.87	4,137	255
CA	31.40	73.00	6.71	41.04	5.41	1.49	0.78	50.16	4,056	266
EA	28.66	72.97	6.22	40.97	5.38	1.55	0.70	50.59	4,119	260
SEA	28.17	73.06	6.71	40.77	5.37	1.80	0.60	49.33	4,063	273
Turkey	28.32	73.32	6.14	40.98	5.39	1.55	0.72	50.48	4,107	260

*Dry waste amount

on the amount of dry gas, the moisture and the outlet heat were all computed using the empirical formula formed in accordance with the tables given by Tchobanoglous and Kreith (2002). The additional heat requirement became zero if the outlet temperature was equal or higher than the desired outlet temperature (T_D). In the contrary, if it was lower, then the additional heat requirement should be calculated. The amount of supplementary fuel, the air required for burning and the dry gas and moisture production due to the incineration of supplementary fuel were all estimated in the next step. The unit of supplementary fuel amount (SF) should be in gal/h according to the empirical formula in the algorithm. The desired outlet temperature was assumed as 1,100°C (2,012°F) to minimize the hazardous pollutant concentration at the outlet of the incinerator as applied in Europe, especially if halogenated compounds needed to be removed (Rogoff et al., 2019). Here, fuel oil was chosen as the supplementary fuel, therefore, unit air requirement to burn supplementary fuel ($UA_{R,SF}$) was estimated as 14.9 ton/m³ (125.06 lb/gal for the calculation), unit dry gas production due to supplementary fuel incineration ($UDG_{P,SF}$) as 15 ton/m³ (125.54 lb/gal for the calculation) and unit moisture production ($UM_{P,SF}$) due to supplementary fuel incineration as 1,048 kg/m³ (8.75 lb/gal for the calculation) and, the heat sourced by the supplementary fuel was calculated with the empirical formula designed using the tables given by Tchobanoglous and Kreith (2002). Thus, the outlet heat was increased up to the level equal to the desired outlet temperature. At the same time, the dry gas and moisture leaving the incinerator were also increased due to the addition of the supplementary fuel.

3.2.1.3. Steam production

At the next step the estimation started with the amount of steam to be produced after the incinerator (Bottom left-hand side of the Algorithm given in Appendix A1). First, boiler outlet heat was computed by using the amount of dry gas and moisture leaving the incinerator. The boiler outlet temperature (T_{BO}), which should always be higher than the steam temperature (T_S), was presumed as 415°C (780°F) (Tchobanoglous and Kreith, 2002). The waste heat to be recovered was determined by subtracting the radiation losses (RL%) in the boiler system, assumed as 1% of the total heat. At the second step the calculation focused on the various enthalpy values at different points of steam production units at different temperatures. Here, the empirical formulas were defined in accordance with the tables given by Tchobanoglous and Kreith (2002). The steam temperature was assumed as 350°C (660°F), discharge water temperature (T_{DW}) as 350°C (660°F), feed water temperature (T_{FW}) as 105°C (220°F), condense temperature (T_C) as 77°C (170°F) and the temperature of the water entering to the deaerator (T_{DA}) as 15°C (60°F) (Tchobanoglous and Kreith, 2002).

All flows, covering feedwater, gross steam, additional water, the steam flow needed to heat feed water and the recoverable steam, were analyzed before energy recovery calculations using the enthalpies and the pre-calculated waste heat.

3.2.1.4. Energy recovery

At the final step, the pressure of the produced steam before steam turbine (PS) was assumed as 0.75 MPa (110 lb/in²), the pressure of steam after turbine (P_{SE}) as 10 kPa (1.45 lb/in²), and the temperature of steam after turbine (T_{SE}) as 105°C (220°F). Thus, the specific enthalpy of steam before turbine $H_{S,Sp.PS,TS}$ was 3.16 MJ/kg and the specific enthalpy of steam after turbine $H_{S,Sp.PSE,TSE}$ was 2.68 MJ/kg (TLV, 2020). Specific electricity and thermal energy recovery potentials were assessed by assuming the total turbine efficiency (Y_{Tbn}) in a range of 55 to 60% depending on the turbine selection.

3.2.2. Gasification

Gasification is the conversion of biomass to a gaseous fuel called as syngas, through gas-forming reactions realized in an oxygen-deficient environment (Xu et al., 2017). Energy recovery from waste through the gasification process depended on obtaining the quality and quantity of the syngas generated, by completing the simulation on ASPEN Plus software, as shown in the detailed algorithm in Appendix A2.

In ASPEN, H_2O, N_2, O_2, S, H_2, H_2S, NH_3, CH_4, C (solid), CO and CO_2 parameters were defined as conventional materials, and WASTE and ASH parameters were defined as non-conventional materials. WASTE input was defined depending on the elemental, proximate and sulfur analysis results and the HHV of waste. The elemental analysis of the waste involved C, H, N, Cl, S, O and ash content (AC), where all components add up to 100%. Proximate analysis consists of moisture content (MC%), fixed carbon content (FC%), volatile matter content (VM%) and the AC%. Lastly the sulfur analysis consists the pyritic sulfur, the sulfate and the organic sulfur contents of waste equal to S% of waste. Thermal dewatering up to 15% moisture was applied to mixed livestock waste as the same in the incineration.

3.2.2.1. Simulation environment on ASPEN

The simulation in ASPEN covered following assumptions (Ramzan et al., 2011): (i) All reactions were in a steady state.

(ii) The whole system was isothermal. (iii) All sulphur producing reactions would form H_2S. (iv) NH_3 was the only nitrogen-based compound to be formed during gasification process. (v) There would not be any oxidized nitrogen. (vi) N_2 could be observed at the outflow as a result of atmospheric air usage as an oxygen source. (vii) Whole reactions would occur in ideal conditions. Thus, gasification modelling was done by using Redlich-Kwong-Soave (RKS) cubic equity thermodynamic conditions, which had been proven for high temperature waste pyrolysis and gasification calculations (Deng et al., 2017).

The flowchart of the gasification process was shown in Figure 2a and in Appendix A2.

DRY-REAC was the first reactor of the system representing the drying process, simulated by a FORTRAN statement where pre-coded RStoic reactor type was used. It was accepted that a completely dry waste was achieved at the end.

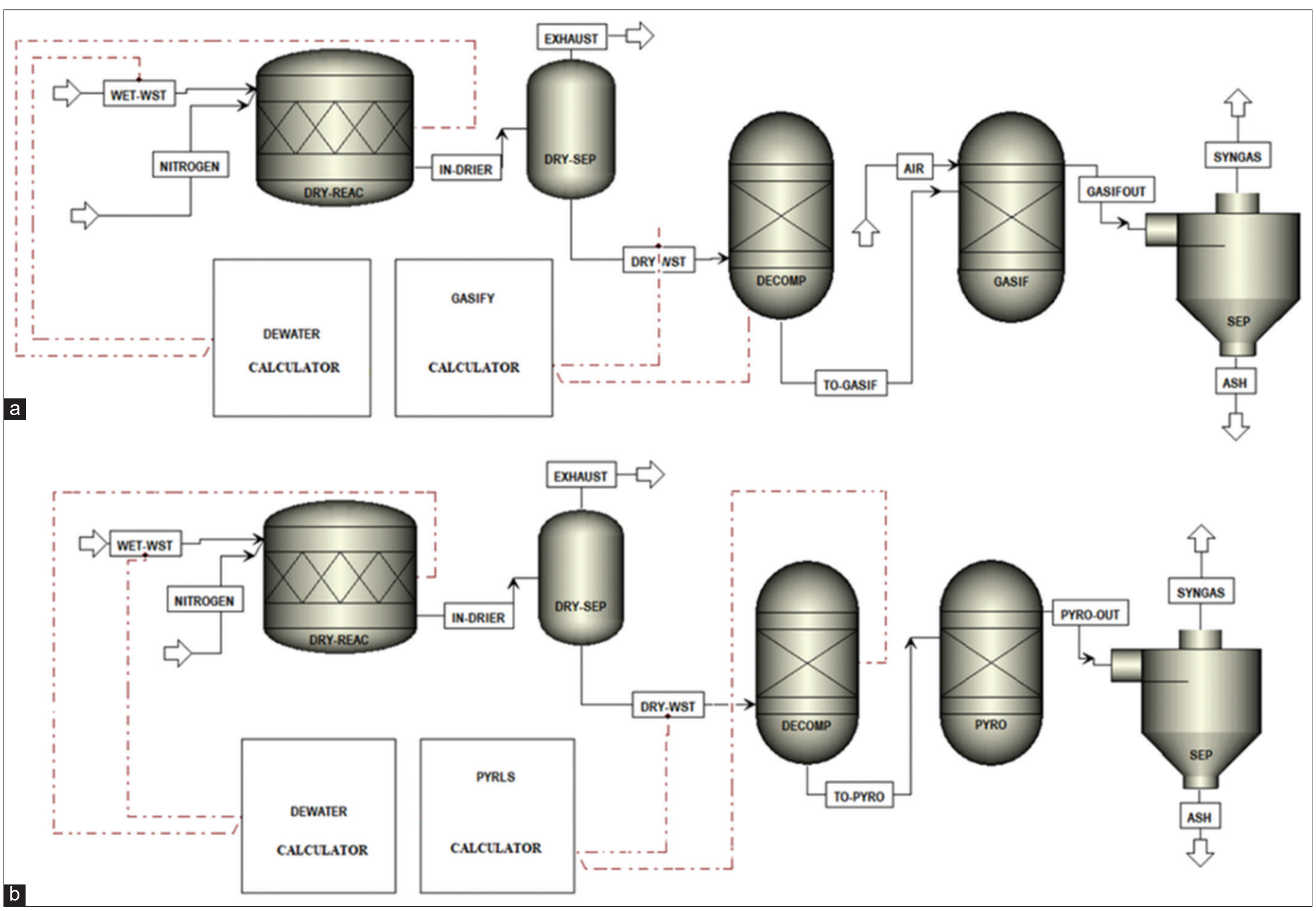
DRY-SEP was the second reactor block of the system where separation of solid and liquid phase was expected after drying. ASPEN Plus's Flash2 block was used at this stage. In real operational conditions, *DRY-REAC* and *DRY-SEP* are used as a single reactor. However, it was defined in two separate reactors in modelling environment. In on-site application conditions, drying and gasification phases may also be preferred to applied in a single reactor. Yet, it was determined to be applied in separate reactors in the modelling calculations to have the most accurate results.

DECOMP was the third reactor block of the system where the dried waste was decomposed to the main end products. In this RYield reactor, the solid material fed into this block split into C, H, N, O and S within respect to the molecular formula of the waste. A FORTRAN statement was defined to determine the amount of each element in accordance with the ultimate analysis of waste.

GASIF was the fourth reactor block of the system where the simultaneous gasification reactions produced CO_2, H_2O, CO, H_2, CH_4, NH_3 and H_2S (Ramzan et al., 2011). RGibbs reactor was used to simulate gasification reactions inside the reactor. In real operational conditions, *DECOMP* and *GASIF* reactor block work as a single reactor and whole reactions occur simultaneously. Modelling preferred a separate reactor evaluation to outline more accurate results. A sensitivity analysis on syngas composition was done between 550 to 1000°C with an increase of 50°C, determining the change of heating value of produced syngas, so that the optimum operational temperature of the reactor could be decided. Based on this analysis, the reactor temperature was chosen as 750°C at a 0.3 air/waste ratio.

SEP was the fifth reactor block of the system where the separation of solid and gas phases was expected, where the mass distribution of syngas ingredients (H_2O, N_2, H_2, H_2S, NH_3, CH_4, CO, CO_2) was

Figure 2: Flow charts on ASPEN plus software: (a) Gasification, (b) Pyrolysis



obtained. SSplit reactor was used as recommended by ASPEN Plus guidance documents.

3.2.2.2. Energy recovery

Combustible ingredients in syngas with different heat values were revealed as H_2 with 39.5 kWh/kg (142,081 kJ/kg), CH_4 with 15.38 kWh/kg (55,384 kJ/kg), NH_3 with 6.25 kWh/kg (22,500 kJ/kg), H_2S with 4.83 kWh/kg (17,396 kJ/kg) and CO with 2.82 kWh/kg (10,160 kJ/kg) (Wang et al., 2013; The Engineering Toolbox, 2020). The heat value of syngas was calculated by using the heating values of each combustible syngas ingredients and the mass distribution obtained from the ASPEN Plus Software. In accordance with the syngas engine selection, depending on the technical availabilities on the market, the electrical yield of the system (Y_{ELC}) was assumed as 30% and the thermal yield (Y_{TH}) as 45% of the total heat. These led to the ultimate calculation of the specific electricity and thermal energy recovery potentials. Thermal dewatering up to 15% moisture was applied to mixed livestock waste as the same in the incineration and gasification.

3.2.3. Pyrolysis process

Pyrolysis process is the conversion of the chemical energy of organic materials into mixture of gases, organic liquid molecules, and solid chars by rapid heating of biomass without oxygen (Liu et al., 2020). Energy recovery from waste with pyrolysis process depends on obtaining the quality and quantity of syngas by making simulation on ASPEN Plus software very similar to the gasification process as shown in the detailed algorithm in Appendix A3. Here, only the gaseous output of the pyrolysis process, which is syngas, was assumed to be used for continuous energy recovery purposes, especially for electricity. Thus, oil production from pyrolysis was not considered in the methodology.

3.2.3.1. Simulation environment on ASPEN

The only difference with the gasification process was the reaction temperatures in the pyrolysis reactor and the lack of oxygen in the system. All other assumptions in the system were taken the same as in the simulation of gasification. To simulate pyrolysis reactions, *PYRO* reactor was used instead of *GASIF* reactor, as shown in Figure 2b.

PYRO was the fourth reactor block of the pyrolysis system where the simultaneous reactions occurred to produce CO, CO_2, H_2, CH_4, NH_3 and H_2S (Ramzan et al., 2011). RGibbs reactor was practiced similar to the gasification modelling. In real operational conditions *DECOMP* and *PYRO* reactor block functioned as a single reactor, and whole reactions were realized simultaneously. A sensitivity analysis on syngas composition between 200 to 1000°C for each 50°C difference resulted in the change of heating value of produced syngas. This step was very important to decide on the reactor temperature. As a result, the gross energy yield of syngas increased by increasing the reactor temperature more than 300°C. Yet, the increased rate of energy yielded decreased up to the 550°C reactor temperature. Above 550°C, the gross energy tended to increase due to the increase of H_2 fraction in syngas. However, the impact of CH_4 to the syngas' gross energy decreased. Therefore, it was decided to use a reactor temperature between 550°C and 750°C to obtain the optimal and high temperature results.

The mass distribution of syngas ingredients (H_2O, N_2, H_2, H_2S, NH_3, CH_4, CO, CO_2) were obtained as in gasification.

3.2.3.2. Energy recovery

Similar to the modelling of gasification, the heat value of syngas was calculated by using the mass distribution resulted from the ASPEN Plus Software. The heating value of each combustible syngas ingredients, and again in accordance with the syngas engine selection depending on the technical availabilities on the market, the electrical yield of the system was assumed as 30% and the thermal yield as 45% of the total heat. Thus, specific electricity and thermal energy recovery potentials were calculated.

3.2.4. Anaerobic digestion process

Anaerobic digestion as a widely acknowledged sustainable waste treatment technique is broadly used to generate a high-value gaseous product by the decomposition of waste under an environment without oxygen, converting the organic matter to biogas through microbial activities (Achinas et al., 2019). Modeling of the anaerobic digestion in this study depends on the estimation of the methane generation potential of waste based on different analysis results, as shown in the detailed algorithm in Appendix A4.

3.2.4.1. Calculation of biogas production

The first step to estimate the biogas production was to check the specific methane potential of the waste. If any experimental result was available on specific methane potential, then it was possible to calculate waste specific methane production. Otherwise, it needed to be estimated using the elemental analysis of the waste. Once the molecular formula was defined, COD equivalent of waste was theoretically calculated by setting up the chemical equilibrium. The COD removal efficiency of anaerobic treatment was mostly linked with Volatile Solids (VS) destruction. Following the algorithm, the specific methane potential was calculated by assuming a VS destruction rate from literature or using the result of an analysis devoted to this particular waste.

To have more accurate results with the mixed livestock waste, in this study, it was decided to calculate specific methane generation potential by using the molecular formula of mixed livestock waste instead of using the experimental results found in the literature.

An estimation on methane percentage of biogas (r_{CH4}) led to the total amount of biogas. Only methane was considered as a flammable ingredient in biogas that serves to the energy recovery.

3.2.4.2. Energy recovery

Similar to the modelling of pyrolysis and gasification, the heat value of biogas was calculated by using the heat value of combustible biogas ingredient, which was methane. Pure methane has a heat value of 11.06 kWh/m³ (39,800 kJ/m³) (Jørgensen, 2009).

The heating value of biogas differs between 5.55 kWh/m³ and 7.22 kWh/m³ depending to its composition and methane content in a range of 50% to 65% (National Institute of Food and Agriculture, 2019). Mostly, a methane content of 60% was assumed in biogas, leading to a heat energy of 6.62 kWh/m³ of biogas.

In accordance with the biogas engine selection, depending on the technical availability on the market, the electrical yield of the system was assumed as 35% and the thermal yield as 45% of the total heat for the calculation of the specific electricity and thermal energy recovery potentials.

4. RESULTS AND DISCUSSION

The methodologies defined for four different processes were applied to mixed livestock wastes generated in Turkey to achieve the highest energy recovery possible. The results of the simulations were evaluated on the basis of $E_{ELC,Sp}$ and $E_{TH,Sp}$ to indicate the energy potential converted to electricity and heat, respectively. Energy recovery potentials were summarized for different regions and also for Turkey as a whole in Table 8.

A significant point of interest by the results was the observation that the unit electrical energy generation with thermal technologies was quite high if compared with the biological processes. In contrary, the unit thermal energy recovery rate with thermal technologies was quite low if compared with the biological technologies due to the high energy requirement for dewatering process prior to energy recovery process. Negative values shown in Table 8 indicated the requirement of additional thermal energy to achieve the desired dewatering level which was not a prerequisite for anaerobic digestion.

Incineration demonstrated a recovery rate between 0.38 MWe/t to 0.46 MWe/t for different regions, the lowest for Aegean and the highest for Central Anatolia if converted to electricity. The similar tendency was also observed when the heat energy was recovered, the lowest in recovery rate was achieved in the Aegean region as 0.05 MWth/t and the highest in the Central Anatolia region as 0.21 MWth/t. The application of incineration process lead to a recovery ratio of 8.9 ± 0.9% as electricity from mixed livestock waste if compared to the initial LHV of the raw waste.

The energy recovery rates with gasification process have shown similar distribution along with the regions compared to incineration, with 21% less electrical energy recovery in Turkey average. The unit recovery rates differed in a range of 0.30-0.38 MWe/t; lowest for Aegean and highest for Central Anatolia. The negative values for Marmara, Aegean and Mediterranean regions in heat energy recovery section resulted from the excessive need for dewatering energy. Gasification process revealed a recovery rate of 7.1 ± 0.8% on electricity based on the initial LHV of raw waste.

Pyrolysis, as one of the energy recovery alternatives, was applied at two different temperatures, 550°C and 750°C. Pyrolysis at 750°C reflected approximately 50% higher recovery rates in terms of electrical energy recovery. It was important to note that the desired level of dewatering always needed an external (auxiliary) heat energy for pyrolysis at 550°C.

The energy recovery rates fluctuated between 0.13-1.17 MWe/t, if transformed into electrical energy. The rates were identified as 0.28 MWe/t for Aegean and 0.35 MWe/t for Central Anatolia. The pyrolysis presented an electrical recovery rate of 0.15 MWe/t for mixed livestock waste as an average for Turkey; these rates were increased up to 0.31 MWe/t at 750°C reactor temperature. The pyrolysis at 550°C provided a recovery of 3.2 ± 0.4% in terms of electrical energy, it was approximately doubled to 6.6 ± 0.8% at 750°C.

The biological technology, anaerobic digestion, on the contrary to thermal technologies indicated a higher recovery rate on heat energy because there was no need for the dewatering step at the beginning. In this case, recoveries of electrical and heat energy fluctuated between 0.19-0.24 MWe/t and 0.24-0.30 MWth/t, respectively (lowest for Aegean and highest for Central Anatolia). The anaerobic digestion process provided a recovery rate of 4.4 ± 0.5% as electricity when compared with the LHV of the raw mixed livestock waste.

The evaluation of the thermal technologies clearly indicated that incineration reflected the maximum yield where the pyrolysis at lower temperature remained at the lowest performance. The increase in the pyrolysis temperature directly resulted in an increase of recovery rate. Pyrolysis at higher temperatures performed close to gasification about 8% less. The reason for obtaining higher recovery rate for incineration in comparison to gasification and pyrolysis was hidden in the higher calorific value of raw waste before it was converted into a semi-product, syngas.

The results indicated that the unit electrical energy recovery rate for all thermal technologies was always the lowest for Aegean and the highest for Central Anatolia among other regions. This finding can be explained by the characteristics of the wastes forming the mixture. In Aegean, the livestock waste was mainly consisted of cattle manure with quite low contribution of sheep and goat manure. As seen from Table 5, the lower calorific value of cattle manure was noticed to be higher than the sheep and goat manure, but the dry matter content of cattle manure was found lower than the others. The lower calorific value of the mixture in Aegean was

Table 8: Energy recovery potential of mixed livestock waste in different regions and countrywide by different technologies

	$E_{ELC, Sp.}$ (MWe/t)					$E_{TH, Sp.}$ (MWth/t)				
	Inc.	Gas.	$P_{@550°C}$	$P_{@750°C}$	AD	Inc.	Gas.	$P_{@550°C}$	$P_{@750°C}$	AD
Marmara	0.40	0.34	0.15	0.31	0.19	0.08	−0.02	−0.30	−0.06	0.24
Aegean	0.38	0.30	0.13	0.28	0.19	0.05	−0.04	−0.29	−0.07	0.24
Black Sea	0.45	0.35	0.16	0.33	0.22	0.18	0.08	−0.22	0.04	0.28
Mdt.	0.40	0.31	0.14	0.29	0.19	0.09	−0.01	−0.27	−0.05	0.25
CA	0.46	0.38	0.17	0.35	0.24	0.21	0.13	−0.18	0.08	0.30
EA	0.43	0.34	0.15	0.31	0.21	0.15	0.05	−0.23	0.01	0.27
SEA	0.42	0.33	0.15	0.30	0.22	0.13	0.03	−0.24	−0.01	0.28
Turkey	0.43	0.34	0.15	0.31	0.21	0.14	0.04	−0.24	0.00	0.27

slightly higher than the waste mixture in other regions. Thus, the dry matter content had more significant effect on the energy output than the lower calorific value of raw waste since that a certain part of the internal energy of waste was initially consumed for the evaporation of the water content. A contrary case was observed in Central Anatolia, with a mixture having lower calorific value but higher dry matter content.

In 2018, the year in which the livestock waste inventory was evaluated, electricity consumption in Turkey was 301,216 GWh/year (EMRA, 2020). The results of this study outlined that 66,499 GWh/year electrical energy can be potentially generated by using incineration if all produced livestock waste were collected and utilized. This amount constitutes 22% of the consumed energy in the same year. Gasification ended up with an output of 52,385 GWh/year as 17% of the total consumption close to gasification efficiency. Pyrolysis technology as one of the thermal technologies served a much lower energy of 23,153 GWh/year at 550°C and almost doubled to 48,146 GWh/year at 750°C. The anaerobic digestion as a biochemical technology yielded an energy of 32,331 GWh/year, almost half of the incineration and gasification providing approximately 10% of the total energy consumption.

67% of electricity production in Turkey is provided from conventional sources, renewable energy sources are only 35% realized. Coal and natural gas consisted more than 99.5 % of electricity generation with conventional sources (113,248 GWh/year and 91,639 GWh/year respectively) (EMRA, 2020). The unit fuel consumption is reported as 0.50 kg/kWh for coal fired electricity generation plants and as 0.20 m^3/kWh for natural gas fired plants (Energy Information Administration, 2021). Therefore, full recovery of livestock waste with the most efficient technology means 34 million ton less coal or 13 billion m^3 less natural gas annual consumption.

The emissions emitted from coal fired and natural gas fired electricity generation plants are stated as 760 gCO_2eq/kWh and 370 gCO_2eq/kWh, respectively (Schlömer et al., 2014). Energy recovery from livestock waste to electricity generation will also contribute air emission reduction on total emissions, approximately 86 million tons from coal and 34 million tons from natural gas sourced power plants.

5. CONCLUSION

From a practical standpoint the study outlined an issue of prime importance in the recovery of energy from livestock waste. Recovery from waste is essential in terms of reducing the environmental impacts on the one hand and creating a value-added end product on the other, both serving to the concept of sustainable environment and Green Deal approach.

The analysis proved that an energy recovery in a range of 15-22% is possible with the thermal technologies, whereas this ratio is limited to 10% with anaerobic digestion. The vital bottle neck to reach the potential energy recovery is strictly depending on the efficient compilation of livestock waste and preparation for energy recovery facilities. It should be considered that the overall energy conversion efficiency of the waste-to-energy technologies is strongly affected by the waste supply impacted by the distance and the rate accessible during the year. Strategies should be developed to have the most appropriate management scheme to have the highest economic benefits.

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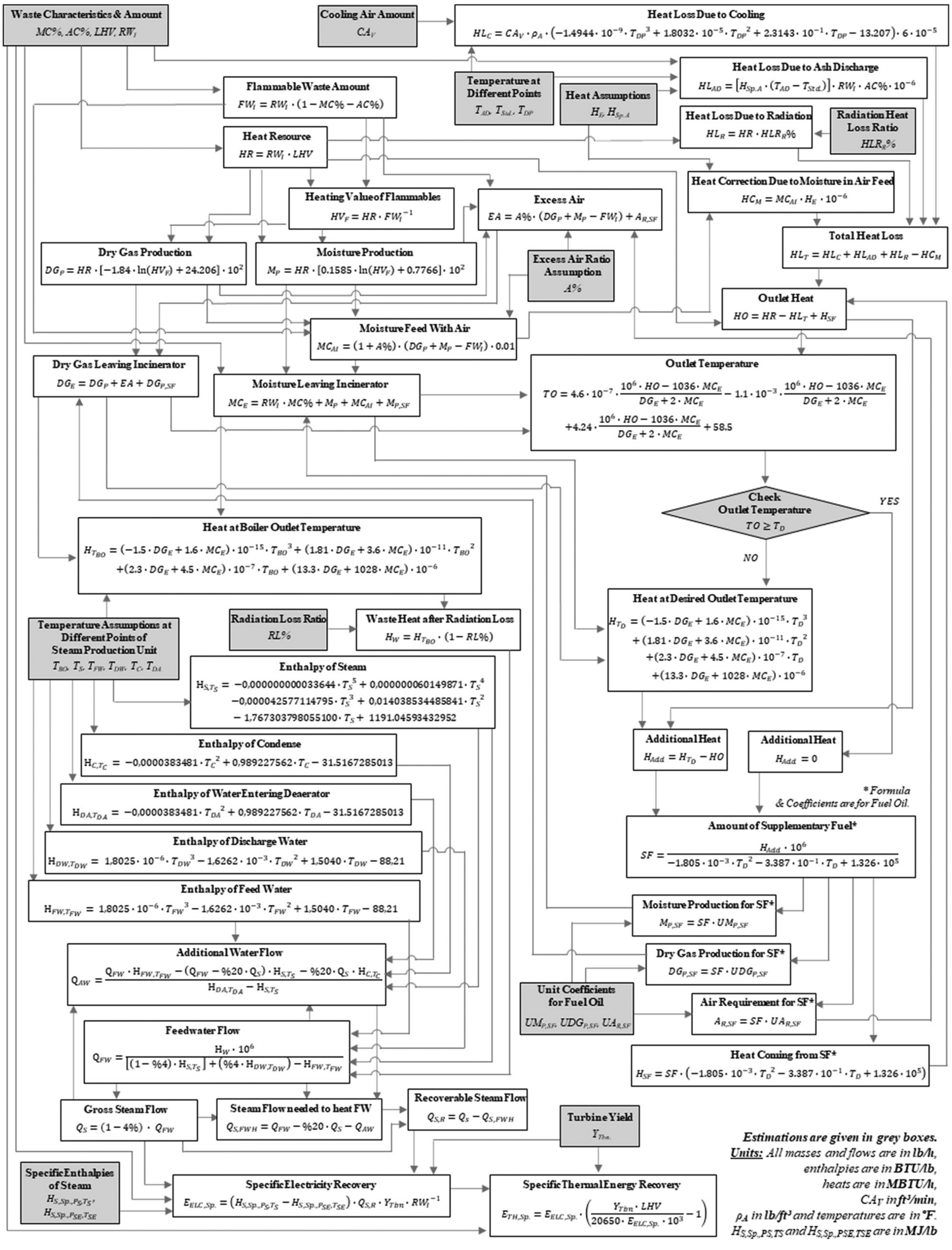
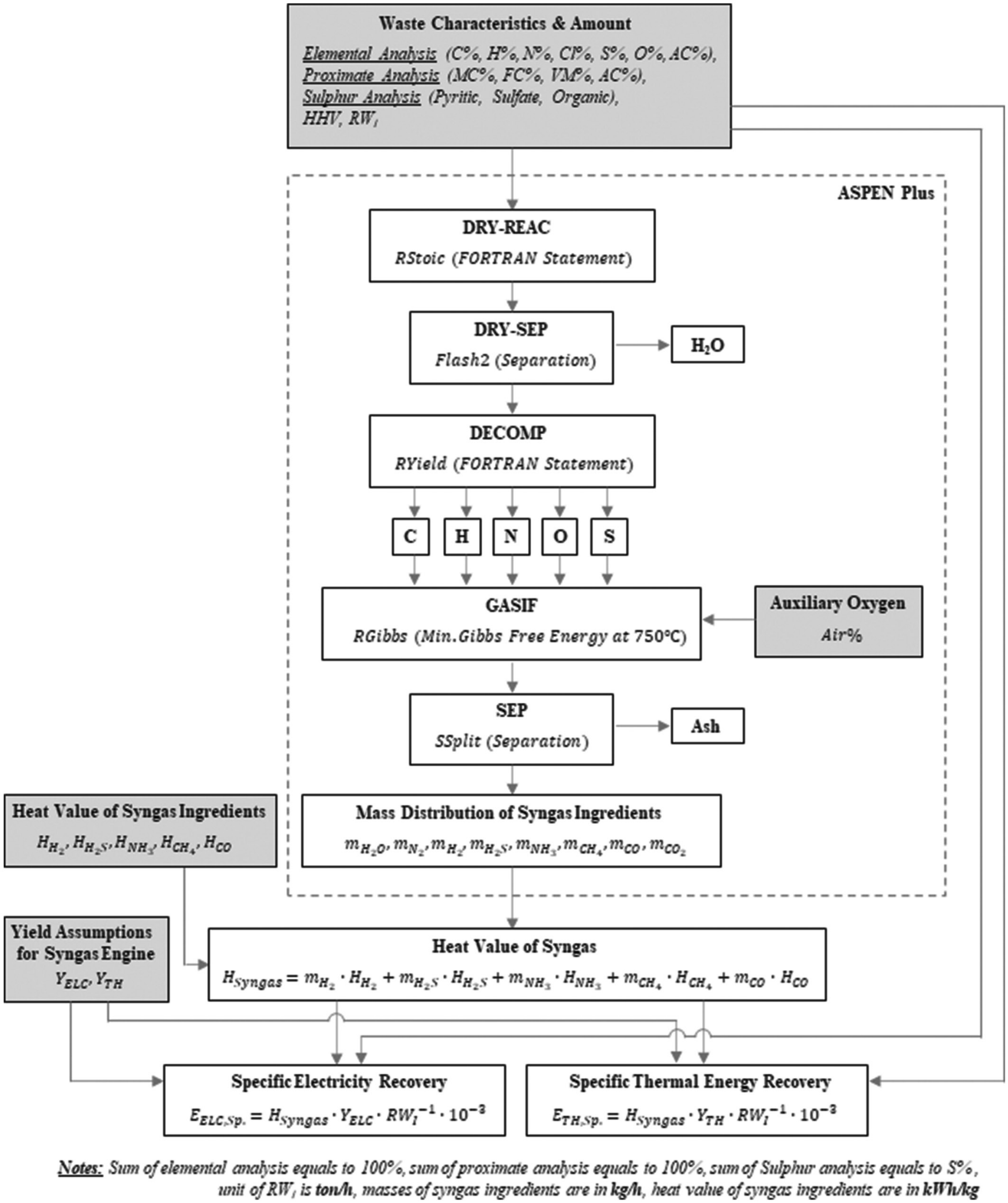
APPENDICES

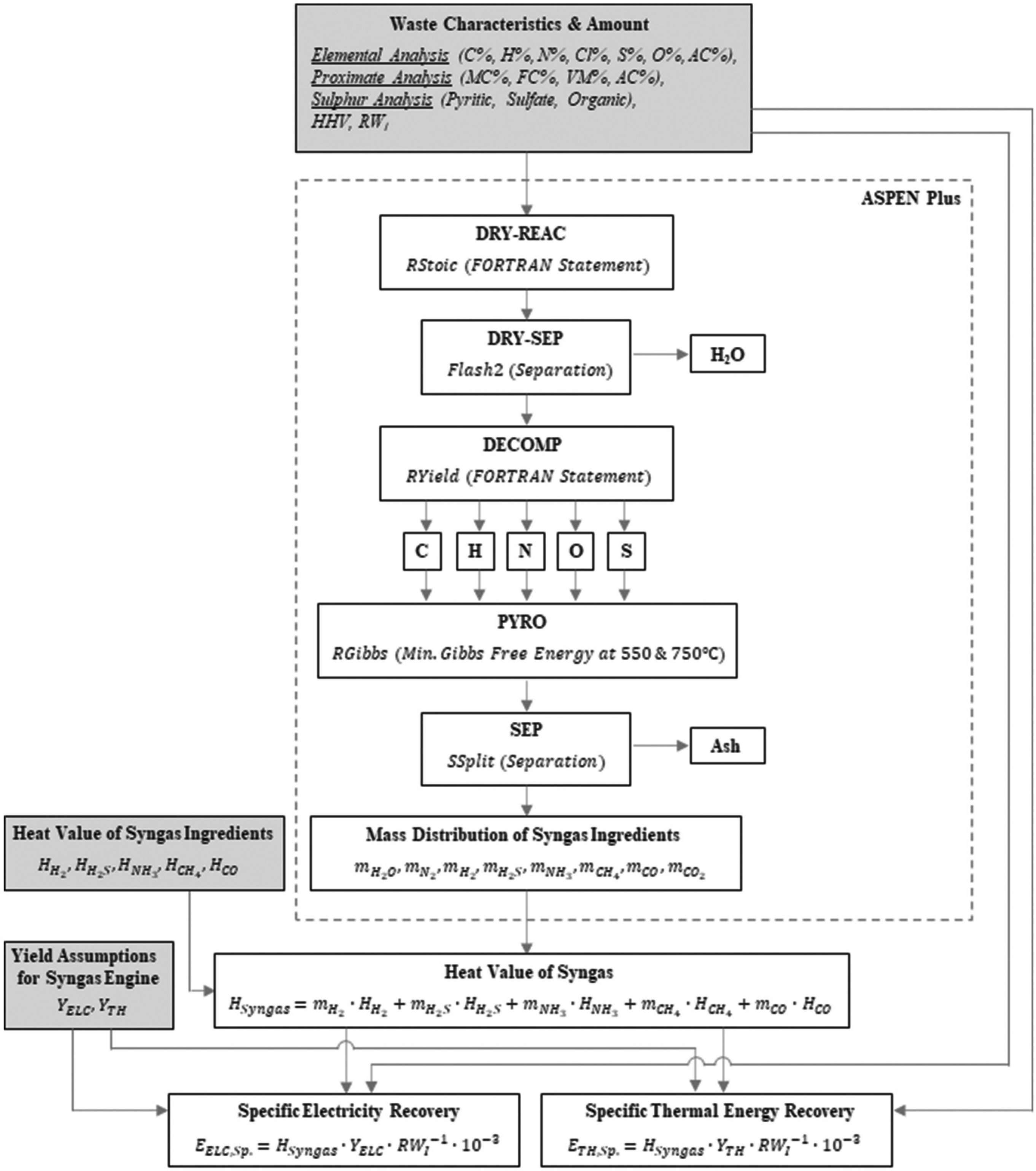
A1 – Incineration Model Algorithm



A2 – Gasification Model Algorithm



A3 – Pyrolysis Model Algorithm



Notes: Sum of elemental analysis equals to 100%, sum of proximate analysis equals to 100%, sum of Sulphur analysis equals to S%, unit of RW_I is **ton/h**, masses of syngas ingredients are in **kg/h**, heat value of syngas ingredients are in **kWh/kg**

A4 – Anaerobic Digestion Model Algorithm