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Pollutants production, energy recovery and environmental impact of sewage sludge co-incineration with biomass pellets

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A B S T R A C T

This study describes the production of pollutants, energy recovery and environmental impact of the co-incineration of sewage sludge and biomass pellets. The main objective of this study is to describe the use of energy generated by co-incineration and to assess the environmental impact of emitted pollutants. Co-incineration takes place in five different blended. The combustion takes place in a fluidised bed reactor with an average combustion temperature of 915–939 °C. The combustion process is mapped by Fourier transform infrared spectroscopy, Continuous Mercury Monitoring Systems, thermocouples, pressures, and flows sensors. The results show that the concentrations of harmful substances, namely SO_2 and NO_X, reach values of 12.39–1730.33 $mg{\bullet}m_N^{-3}$ for SO_2 and 93.30–1156 $mg{\bullet}m_N^{-3}$ for NO_X. This means that the emission limits are exceeded 40 times for SO_2 and 8 times for NO_X in the worst case. Regarding heat recovery, the resulting value of potential energy recovery from the flue gas is 5.35–7.69 $MJ{\bullet}kg^{-1}$, and as the sewage sludge content in the fuel increases, the heat recovery value decreases. The resulting values of pollutant concentrations are also analyzed using a life cycle assessment approach using the GaBi software. The results show that sewage sludge incineration has the greatest impact on climate change, terrestrial ecotoxicity, and human toxicity. Again, as the sewage sludge content in the fuel decreases, the hazardousness of the discharged flue gas decreases. This study presents a relatively promising option to use sewage sludge as a secondary fuel in large combustion sources under certain conditions.

1. Introduction

Sewage sludge (SS) is a by-product from wastewater treatment plants that is characterized by its high nutrient and energy content. However, at the same time, due to its content of organic compounds and heavy metals, it may be a potential danger to the human body (Dewil et al., 2006; Ramos and Fdz-Polanco, 2014). In the European Union, the production in 2017 was 9.5 million tonnes of dry matter (DM) of SS. In the same year, 192,000 tonnes of SS DM were produced in the Czech Republic, with similar production expected in the future. In addition, the system of disposal of SS has been changing in recent years. The energy use of SS significantly increased year-on-year by 14%. The use for incineration increased by 3.3% and for composting by 11.8%. Even in the case of incineration, sewage sludge recovery rates increased nearly 10 times between 2015 and 2020 (Czech Statistical Office, 2022).

The energy recovery potential of SS consists of two main parts: anaerobic digestion (Duan et al., 2012) and usage in thermal

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processes such as pyrolysis (Dziok et al., 2021), gasification, or incineration with energy recovery (Samolada and Zabaniotou, 2014).

The landfill environmental issues such as significant land demand, and leachate production are difficult to deal with and impact the groundwater (Xu et al., 2018). Incineration, on the other hand, is a more acceptable option, because of the reduction in the volume of the original material and the elimination of pathogens and other organic matter (Fytili and Zabaniotou, 2008). Incineration of SS is a very widespread treatment method in recent times. Specifically, in the USA, 170 SS incineration plants are in operation (United States Environmental Protection Agency, 2022). The low heating value (LHV) of the dry SS is 12–16 MJ•kg^{-1} (Wzorek, 2012). However, high moisture content (up to 80 wt%) implies that a large amount of energy is consumed to evaporate the moisture (Xu et al., 2018). At the same time, the nitrogen content of SS is higher than in other fuels, leading to higher emissions of NO_x (Van Caneghem et al., 2016).

Murakami et al. (2009) described the incineration characteristics of sewage sludge in the pressurized bubbling fluidised-bed combustor. The incineration temperature was approximately 1200 K. CO and N_2O concentrations increased in response to decreasing O_2. On the contrary, as temperature increased, CO concentrations decreased simultaneously with the decrease in N_2O concentrations. Liang et al. (2021) investigated the possibility of incineration of wet and dried SS after mechanical dewatering with additional drying to a moisture level of 10–30 wt%. They demonstrated some limited possibilities of burning SS, both wet and dry, however, the amount of energy consumed for drying is significant. Donatello and Cheeseman (2013) developed a typical SS incineration technology where a mechanical dehydrator and dryer were installed before the combustor. Another option for the SS thermal utilization is the co-incineration which is widely used for different kinds of materials (Ryšavý et al., 2023), beech leaves (Ryšavý et al., 2021b), invasive acacia (Vicente et al., 2019) species, or palm kernel shells (Pawlak-Kruczek et al., 2020) is another option for SS thermal utilization. In practice, co-incineration of SS was tested in different blended ratios with coal (Hong et al., 2013a), biomass (Kijo-Kleczkowska et al., 2016), leather wastes (Zhan et al., 2019) municipal solid waste (Werther and Ogada, 1999) or paper mill sludge (Jadlovec and Honus, 2021). The motivation for co-incinerating SS with another primary fuel is to replace a portion of the primary fuel, save operating costs, and energetically recover SS from landfilling (Ricciardi et al., 2020). Also, this study is intended to show the way that co-incineration is an alternative way to utilize the energy potential of sludge and at the same time is able to incinerate this fuel on a fluidised bed boiler without major limitations.

In the case of this study, the environmental impact assessment describes the impact of the production of SS and biomass pellets (BP) with a subsequent assessment of the production of harmful substances from co-incineration and their impact on the environment. Lundin et al. (2004) described an environmental and economic assessment of sewage sludge handling options. Their results showed that co-incineration of SS is optimal for energy recovery, but it could be costlier and support the production of pollutants. In contrast to other studies that provide only a narrowly defined view of the co-incineration of sewage sludge with primary fuel, this study provides a comprehensive understanding of how a portion of the primary fuel can be replaced by a secondary fuel, in this case sewage sludge. The limits of sewage sludge co-incineration are described in this study, especially due to exceeding emission limits, and increasing environmental and human health impacts. Increasing the content of sewage sludge as fuel leads to a significant burden on ash management, as the ash content of sewage sludge is up to 100 times higher than that of biomass pellets.

Within the scope of this paper, SS and BP were applied in a fluidised bed combustor for co-incineration. Both original materials were transformed into pellet form before incineration and subjected to the ultimate and proximate analyses with ash and water determination. This study also describes the composition of the flue gases, the energy recovery potential of SS, and its subsequent environmental impact. In this study, the method of incineration of SS both pure and mixed with BP is considered. At the same time, the recovery of SS leads to the development of a circular economy. In this study, only pollutant production values enter the LCA. Energy consumption for fuel production is not the primary objective in this study.

To better understand circular economy the Life Cycle Assessment (LCA) is often used as a tool (Výtisk et al., 2022). It is an analytical method for the assessment of the environmental impact of a product, technologies, and services (Kočí, 2009). For a systematic approach, the framework of the LCA consists of four stages: goal and scope definition, inventory analysis, impact assessment, and interpretation (Rebitzer et al., 2004). The literature is from different fields such as food (Vidergar et al., 2021), automotive (Bouter and Guichet, 2022), military (Ferreira et al., 2019), and energy systems (Laurent et al., 2017). Nonetheless, studies that use the systematic approach differ in the scope definition, the functional unit or system boundaries, which render them scarcely comparable. From the scope point of view, the LCA uses three basic approaches, including gate-to-gate, cradle-to-gate, and cradle-to-grave. Despite this fact, the study's holistic view and comprehensiveness often bring limitations and assumptions such as a lack of inventory data (Curran, 2014) in particular. However, there are several review studies that demonstrate the usefulness of the LCA approach. For the SS fuel the LCA review study by Yoshida et. al was conducted (Yoshida et al., 2013). In the field of biomass, the review studies vary depending on the application such as conversion to biofuels (Osman et al., 2021) or technology utilization (Farzad et al., 2016). LCA studies for co-incineration of SS or BP were also conducted (Liu et al., 2023a).

2. Materials and methods

2.1. Sewage sludge production

Before the sewage sludge was processed into its final form for incineration, it was necessary to carry out the dewatering, drying, and pelletizing phases. The raw material was collected at the sewage treatment plant in the Czech Republic with a moisture content equal to 95 wt%. The moisture content after the mechanical dewatering was equal to 84 wt%. This was followed by drying in a paddle batch dryer [24]. The residence time was 60 min, the average temperature was 180 °C and the final moisture of the material was 21.8 wt%. In order to maintain the same properties of the fuels (especially moisture content), the fuels were stored in the fuel preparation laboratory, where the temperature and humidity are kept constant. At the same time, the fuel was stored in airtight containers. Due to the high moisture content of the fuel, which leads to an increased water vapour content in the flue gas, condensation of water vapour on the walls could occur. This phenomenon could distort the results of the experiments. Based on that, the combustion chamber and combustion tract were thoroughly cleaned prior to each repetition of combustion. The dewatering and drying was followed by the pelletizing stage. The process was carried out on an MGB 100 – BONSAI (KOVO NOVÁK, Czech Republic) pelletiser with a capacity of up to 300 kg•h^{-1} and a power input of 6 kW. Consequently, pellets with an individual length of 25 mm and diameter of 5 mm were produced. Appendix A.1 shows the production process of SS pellets. Table 1 describes the composition of SS.

2.2. Biomass pellets production

BP was made from a softwood mixture and was produced on the technology for recycling wood and biomass derivates. A K100 minipellet (Comafer, Italy) pelletiser was used. To compress the sawdust through a matrix into the pellet form, the pelletiser uses two rolls driven by an electric motor. The final product was created with a length of 15 mm and a diameter of 5 mm. Appendix B.1 shows the scheme of the BP production process and Table 1 describes their composition.

2.3. Fluidised bed combustor setup

The experiments were carried out in a fluidised bed combustor. In this pilot-scale unit, the fuel is fed into the combustor by a screw conveyor with a maximum capacity of 4.5 kg•h^{-1}. The heat is generated by an electric resistance heater with a power input equal to 7 kW. Incineration air is supplied from the bottom of the fluidised bed and its maximum flow is 57 m^3•h^{-1}. In this experiment, the incineration air was preheated by a resistance heater to the temperature of 400 °C. The vacuum for the flue gas outtake into the chimney was realized by a smoke fan with a performance of 300 m_n^3•h^{-1}. The fuel supply was ranging from 2.7 to 4.1 kg•h^{-1} with a primary air flow of 31.7–35.0 m^3•h^{-1}. Incineration was performed in the temperature range of 915–939 °C. The resulting values were processed as the average of three one-hour experimental measurements. The measurement error was determined as the Combined Standard Uncertainty - u_C as the sum of the uncertainties A and B. A standard uncertainty. Standard uncertainties type A – u_A are caused by random errors, the causes of which are generally considered to be unidentified. They are determined from repeated measurements of the same value of the measurement under the same conditions. These uncertainties decrease with increasing repetition of the number of measurements (Abdar et al., 2021). Standard uncertainties type B – u_B is caused by known and estimable causes. Their identification and basic evaluation are carried out by the experimenter. Their determination is not always easy. In complex measuring equipment and with increased demands on accuracy, a detailed analysis of the errors must be carried out, which requires considerable experience. These uncertainties come from different sources and the resulting type B uncertainty is given by their sum (Abdar et al., 2021). In this case, all measurements were repeated three times to ensure maximum accuracy and agreement. The overall Combined Standard Uncertainty - u_c of the whole experiment is reflected in Fig. 2, Fig. 3 and Fig. 4 and ranges from 3.72% to 6.84% depending on the type of parameter.

$$u_c = \sqrt{{u_A}^2 + {u_B}^2}[\%] \tag{1}$$

During the operation, the produced fly ash is captured in a cyclone separator and the flue gas is chilled in two coolers, before passing through a filter bag. Thermocouples and pressure sensors are located along the entire height of the device at a 200 mm level stepwise distance (Jadlovec and Honus, 2021). The uncertainty of the thermocouples is ± 2.2 °C and that of the pressure sensors is 0.2%. The schematic view of the reactor is in Fig. 1.

2.4. Energy recovery determination

To determine the additional energy recovery of flue gases from the incineration of SS and BP and based on the equations below, the heat recovery from the incineration of 1 kg of fuel was determined. This represents the amount of energy the incineration gases carry out of the combustor. Calculation of the resulting heat output Q_{fg} was based on the volume of the flue gas V_{fg} and the real flue gas enthalpy $h_{fg,r}$. The real flue gas enthalpy consists of enthalpy of the flue gas and the air. All values were converted to normal conditions, i.e. 101,325 Pa, 273.15 K.

Table 1
Basic properties of SS and BP.

Parameter	Symbol	BP (Ryšavý et al., 2021a)	SS (Jadlovec and Honus, 2021)	Unit	Standard
Carbon	C^r	47.5 ± 1.06	29.07 ± 0.15	% wt.	ISO 16948
Hydrogen	H^r	5.7 ± 0.01	4.04 ± 0.08	% wt.	ISO 16948
Oxygen	O^r	40.3 *	16.53 *	% wt.	ISO 16993
Sulphur	S^r	< 0.1 ± 0.001	0.69 ± 0.02	% wt.	ISO 16994
Nitrogen	N^r	0.1 ± 0.001	2.93 ± 0.08	% wt.	ISO 16948
Water	W^r	6.0 ± 0.01	21.8 ± 0.44	% wt.	ISO 181234–2
Ash	A^r	0.3 ± 0.001	24.94 ± 0.25	% wt.	ISO 18122
Lower heating value	LHV^r	17.7 ± 0.54	9.83 ± 0.34	MJ•kg^{-1}	EN 18125

* Calculated value.

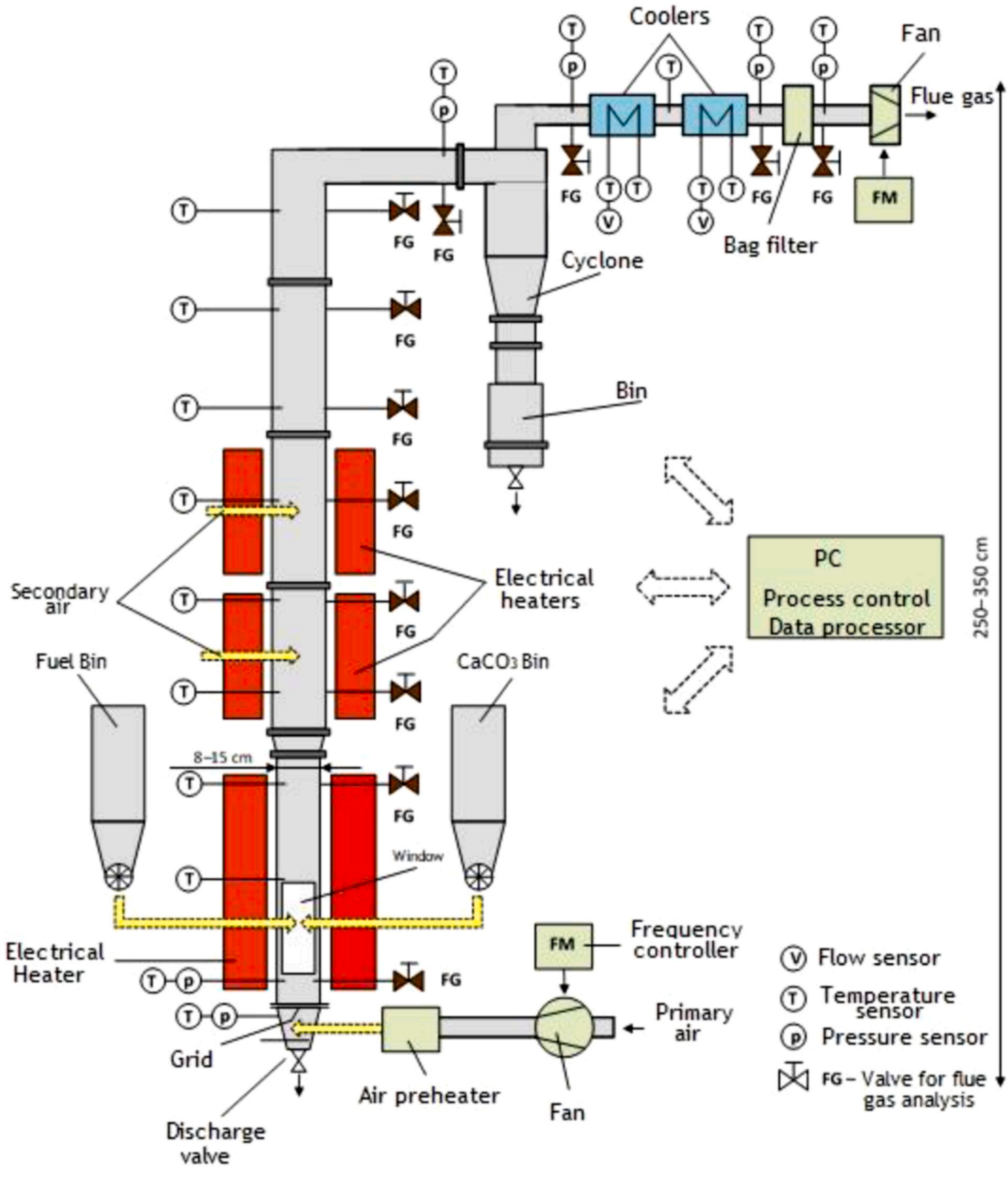

Fig. 1. Fluidised bed combustor (Jadlovec and Honus, 2021).

$$h_{fg,\min,s} = V_{CO2} \bullet h^t_{CO2} + V_{SO2} \bullet h^t_{SO2} + V_{CO} \bullet h^t_{CO} + V_{NOx} \bullet h^t_{NOx} + V_{N2} \bullet h^t_{N2} + V_{CH4} \bullet h^t_{CH4} + V_{NH3} \bullet h^t_{NH3} + V_{HCl} \bullet h^t_{HCl} + V_{HF} \bullet h^t_{HF} + V_{H2O} \bullet h^t_{H2O} + a_{fa} \bullet A^r \bullet h^t_{fa} [\mathrm{MJ} \bullet m^{-3}\mathrm{N}] \quad (2)$$

$$h_{air,\min} = V_{air,\min} \bullet h^t_{air} + (\nu - 1) V_{air,\min} \bullet h^t_{H2O} [\mathrm{MJ} \bullet m^{-3}\mathrm{N}] \quad (3)$$

$$h_{fg,r} = h_{fg,\min,S} + (\lambda - 1) \bullet h_{air,\min}[\mathrm{MJ} \bullet m^{-3}\mathrm{N}] \tag{4}$$

$$Q_{fg} = V_{fg} \bullet h_{fg,r}[\mathrm{MJ} \bullet kg^{-1}\mathrm{N}] \tag{5}$$

where V_{CO2}, V_{SO2}, V_{CO}, V_{NOx}, V_{H2O}, V_{N2}, V_{CH4}, V_{NH3}, V_{HCl} and V_{HF} (-) represent the relative volume fractions in 1 m_N^{-3} of the individual components in the flue gas, h^t_{CO2}, h^t_{SO2}, h^t_{CO}, h^t_{NOx}, h^t_{H2O}, h^t_{N2}, h^t_{CH4}, h^t_{NH3}, h^t_{HCl}, h^t_{HCl} and h^t_{HF} (kJ•m^{-3}) represent the enthalpies of the individual components as a function of temperature, a_{fa} (-) represents the relative fly ash drift, A^r (-) is the relative ash content of the fuel, h^t_{fa} in (kJ•m^{-3}) is the enthalpy of the fly ash and V_{fg} (m^3•kg^{-1}) is the amount of the flue gas generated by incineration of 1 kg of fuel.

2.5. Life cycle assessment

The environmental impacts were evaluated by LCA analytical method which follows the ISO 14040/14044 methodology and standards (Klüppel, 2005). By the principle of ISO 14040/14044 standards, there are no specific guidelines and recommendations on which Life Cycle Impact Assessment (LCIA) method should be used (Výtisk et al., 2023). However, some organizations suggest a specific LCIA method or parts of it (Rosenbaum et al., 2017). This study aims to quantify and compare the environmental impact of SS and BP incineration and their co-incineration. Five options of the fuel blended ratio were evaluated: BP (100%), BP (75%) and SS (25%), BP (50%) and SS (50%), BP (25%) and SS (75%) and SS (100%). The LCIA method chosen for the evaluation of environmental impacts in the individually selected categories was the ReCiPe 2016v 1.1 (H) with midpoint characterization factors commonly used in Europe (Huijbregts et al., 2017). However, the framework of this LCIA method is able to enumerate potential environmental impacts on a wide spectrum of impact categories, both on the midpoint and endpoint level (Výtisk et al., 2020). functional unit (FU) that reflects the energetic potential of the fuel product system is defined as 30 min of incineration which is set based on reaching the required incineration temperatures of 915–939 °C.

The LCAs are usually done as comprehensive and holistic studies of cradle-to-grave type (Výtisk et al., 2022), however, that brings often limitations in the availability of the inventory data. Nevertheless, this study aims specifically at the process of incineration of selected fuel blends in other words at gate-to-gate process. The boundaries are set to input raw materials and the output of pollutants in selected categories.The inventory data of material flows and properties for each blend fuel ratio were obtained by experimental measurement see Table 2. As can be seen from Table 2, only pollutant production values enter the LCA.

The electricity for the auxilliary equipment was not considered in this LCA gate-to-gate type assessment which could be seen as certain limitation of this study.

2.6. Analyses

Ultimate and proximate analyses (UPA) were performed as a complementary data set for fuel evaluation. According to the relevant standards (ISO 29541:2010, ISO 19579:2006, ISO 687:2010 and ISO 1171:2010), the mass concentrations of C^r, H^r, N^r, S^r, O^r, W^r (water) and A^r (ash) were measured in the materials for the raw state. The content of selected elements was determined on the CHNS628 and CHNS628S analysers (both Leco, USA) on the thermogravimetric (Dumas) principle. The amount of O_2 was calculated according to EN 16993 standard was determined as a gravimetric difference after heating the sample above the boiling point of water in a VF110 electric furnace (Memmert, Germany) according to ISO 181234–2. The Ar content was determined in an LEO 5/11 furnace (LAC, Czech Republic) according to the ISO 18122 standard. The lower calorific value (LHV) was determined according to the ISO 18125 standard.

Flue gas was subjected to Fourier transform infrared spectroscopy (FTIR) in an AtmosFIRt gas analyser (Protea, UK) for qualitative

Table 2
Inventory data for different fuel blend.

Fuel blend ratio	BP	BP 3:1 SS	BP 1:1 SS	BP 1:3 SS	SS
Fuel amount [kg]	1.34	1.44	1.55	1.91	2.04
LHV [MJ/kg]	17.7	15.7	13.8	11.8	9.83
Ash content [kg]	0.004	0.093	0.196	0.360	0.510
Flue gases [kg]	12.61	11.67	11.56	12.88	12:61
H_2O [kg]	0.723	0.812	0.909	1.093	1.195
CO_2 [kg]	1.048	1.016	0.988	0.978	0.892
CO [mg]	176	576	633	475	668
NOx [mg]	888	2817	4468	8890	12330
NH_3 [mg]	21	26.4	26.7	30.8	33.0
HCl [mg]	12.1	48.7	141.4	191.2	592.5
SO_2 [mg]	118	3325	7139	14485	18452
CH_4 [mg]	8.5	6.4	7.6	9.9	14.2
C_2H_6 [mg]	1.4	3.4	2.9	5.5	1.3
HF [mg]	5	7	8.6	11.6	19.7
O_2 [kg]	1.708	1.972	2.075	2.384	2.379
Mercury [μg]	7.7	32	46.9	69.2	89.1
N_2 [kg]	9.133	7.867	7.581	8.399	8.112

and quantitative evaluation. This analyser evaluates the amount of CO, CO_2, NO, NO_2, N_2O, NH_3, HCl, SO_2, CH_4, HF and O_2 (Laudal et al., 2003; Wang et al., 2011). The calibration report showed the average error on full scale for each compound. The overall uncertainty value was in the range of 0.1–5.98%. A linearity test was also carried out, which for all compounds met the conditions of EN 15267–3:2007, Annex C. Subsequent mercury analysis was performed on an HM-1400 TRX mercury analyser (Durag, Germany). The value of total mercury was monitored, which represents a sum of elemental mercury and oxidized mercury (Čespiva et al., 2023). The detailed functionality of this analyser is described in the work of Górecki et al. (2016). The relative expanded uncertainty is estimated at 5.5%. Table 3 describes the emission limits for the incineration of SS as waste in the EU.

3. Results and discussion

3.1. Pollutant production from co-incineration

The experiments were carried out in a fluidised bed combustor. Pure SS and BP were incinerated and measured separately and then blended in the ratios 3:1, 1:1, and 1:3. The resulting incineration product, flue gases, were sampled and examined. The flue gas composition was converted to standard conditions, i.e. 101,325 Pa, 273.15 K, dry state, and 11 vol% O_2. The excess air was 1.4. First of all, the excess air was determined based on the combustion equations (McAllister et al., 2011). In addition, the excess air was adjusted based on knowledge of the experimental combustor in order to ensure sufficient fluidisation while providing sufficient oxygen for optimal combustion. Carsky et al. (2022) recommend that the amount of combustion air in a fluidised bed boiler should be in excess of 20–50%.

In the Fig. 2 below the concentrations of the individual flue gas components depending on the fuel type are shown. All pollutants concentrations increased with the increase of SS in the fuel blend. Based on the current commission BAT council implementing a decision by EU 2019, emission limits have been set for the incineration of SS categorized as waste (Union, 2019). The measured data showed that except for the incineration of clean BP, the emission limits as defined in Table 2 were exceeded in all cases and for all measured substances (except NH_3). The NO_x value was determined as the sum of NO, N_2O and NO_2 and represented as NO_2. The NO_x concentration was 93.3–1156.3 mg•m_N^{-3}, which is due to the higher nitrogen content within the fuel, as described by Sänger et al. (2001). These authors also defined an output NO_X concentration in the range of 800–1200 mg•m_N^{-3} for municipal sewage sludge incineration. For CO, the concentration was 18.5–66.1 mg•m_N^{-3} and the introduction of an overfire air (OFA) system could be one of the options for NO_x and CO reduction (Hodžić et al., 2016). Another possibility for a decrease in the mass concentration of CO could be using an oxidation catalyst as a secondary measure (Ryšavý et al., 2022; Vicente et al., 2022). However, for the reduction of high NO_x concentrations (where the OFA system is not sufficient), SNCR denitrification or SCR technology needs to be introduced. The SO_2 concentration was 12.4–1730.3 mg•m_N^{-3}, where Yang et al. (2016) defined the output concentration during SS incineration at 1700 mg•m_N^{-3}. For flue gas desulfurization, it is necessary to involve one of the techniques such as Wet Scrubber - Flue Gas Desulfurization (FGD) (Córdoba, 2015), where its efficiency was tested by Dou et al. (2009) and the results showed that it can reach up to 95% with optimal limestone dosage and optimal droplet size. This technology is also suitable for HCl and HF reduction (Córdoba, 2015). As the proportion of SS in the fuel increased, the moisture concentration in the flue gas increased, which is an undesirable effect from the moisture deposition in the lower atmosphere point of view. Also, the incineration source itself with high humidity flue gas emission will cause an increase in water consumption and will take away too much of the latent heat of vaporization, which is unfavourable to water conservation and heat reuse, as demonstrated by Shuangchen et al. (2017). At the same time, the increasing concentration of acid gases such as HCl (in this case 55 mg•m^{-3} at maximum) HF (1.85 mg•m^{-3} at maximum) together with humidity leads to low-temperature corrosion, as demonstrated by many studies such as Li et al. (2015) or Vainio et al. (2016). As can be seen from the result, as the SS content in the fuel mixture increases, the ash production increases in the range of 0.004–0.51 kg. This leads to a higher impact on the bag filters or electrostatic precipitator, as well as on the impact in the case of a fluidised bed application (Zahedi and Rajabipour, 2019).

Another monitored emission component was mercury. The emission limit is 20 µg•m_N^{-3} (Union, 2019), which was again exceeded for all SS co-incineration, as shown in Fig. 3. Mercury concentrations were 8.1–83.5 µg•m_N^{-3}, which is up to four times the emission limit. Mercury concentrations increased according to a linear relationship $y = 18.108x - 6.8208; R^2 = 0.9901$. Takaoka et al. (2012) also monitored the mercury content of exhaust gas from SS burning plants, with a daily mean value of 40 µg•m_N^{-3} and a maximum value of up to 62 µg•m_N^{-3}. More so, Yasuda et al. (1983) reported that mercury concentration was in the range of 200–400 µg•m_N^{-3}, which is up to five times higher than our results.

Table 3
Emissions limits for SS as waste in EU (Union, 2019).

Pollutants	Unit	Emission limit *
NO_x (as NO_2)	[mg•m_N^{-3}]	150
SO_2	[mg•m_N^{-3}]	40
HCl	[mg•m_N^{-3}]	8
HF	[mg•m_N^{-3}]	1
CO	[mg•m_N^{-3}]	50
NH_3	[mg•m_N^{-3}]	10
Mercury	[µg•m_N^{-3}]	20

* Limits on standard conditions and 11 vol% O_2

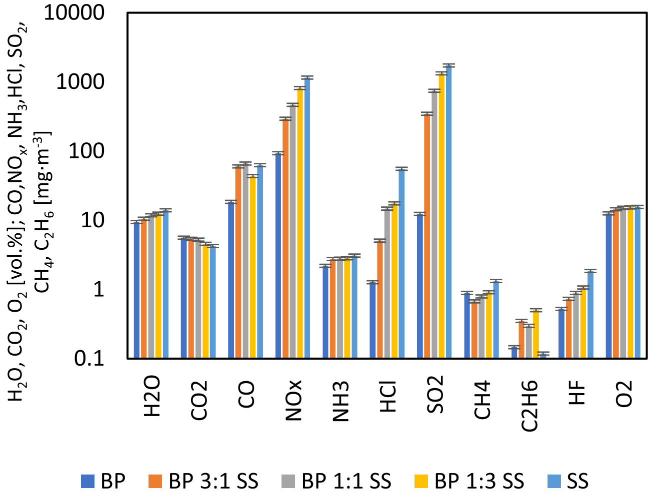

Fig. 2. The concentrations of the compounds in the flue gases.

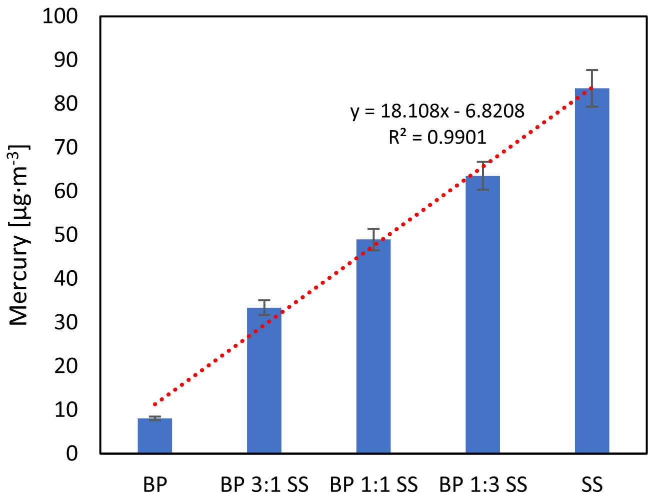

Fig. 3. Mercury concentration in flue gases.

3.2. Energy recovery

In the context of determining the amount of usable energy, the so-called energy recovery was defined depending on the enthalpy of the flue gas and its volume. As can be seen in Fig. 4 below, BP has the highest energy recovery, specifically 7.7 MJ•kg^{-1}. The heat recovery parameter decreases with the increase SS content in the fuel down to 5.3 MJ•kg^{-1}. This occurs in linear dependency according to the equation $y = -0.5951x + 8.3519$; $R^2 = 0.9954$. Depending on the composition, the flue gas volume also decreases with the increase SS content according to the equation $y = -0.4746x + 7.6006$; $R^2 = 1$. The results showed that after the incineration chamber is heated to the required temperature, the fuel is ignited and then burns autonomously without any preheating, except for the preheating of the incineration air to a minimum value of 300 °C. This statement is valid for pure BP and all fuel mixtures except pure SS (lowest Q_{fg} 5.3 MJ•kg^{-1}) where a constant incineration temperature cannot be ensured without fluidised bed heating. In this respect, this paper has made a very sensible proposal to use SS in the sense of incineration and additional energy recovery, but more in the sense of co-incineration with another fuel. A similar increase in energy recovery was interpreted by Lin et al. (2017) who claimed that the blending SS with other solid fuels increases higher reactivity, volatility, and energy content of the flue gases. Wang et al. (2018) illustrated the incineration behaviors of SS blended with pulverized coal. The incineration occurs in a mixture of 5–50% in terms of SS, and the incineration temperature and energy potential of flue gas decrease by up to 30% with the increase of SS content in the fuel. On the one hand, the use of SS in co-incineration can reduce the heat output of the boiler, on the other it can save thousands of tons of coal that would have had to be mined.

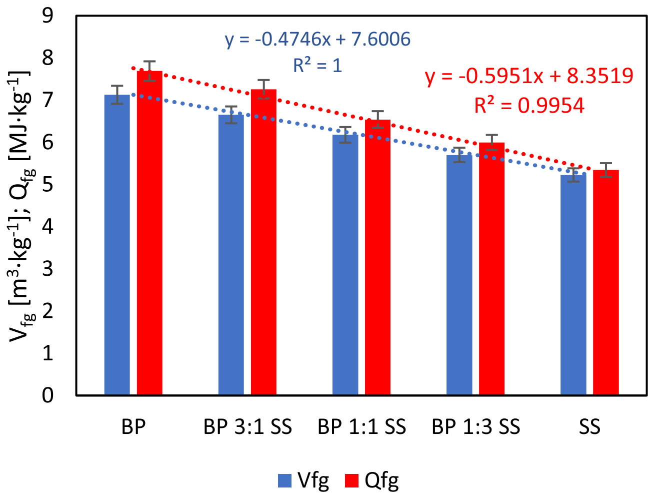

Fig. 4. Heat recovery and flue gas volume.

3.3. Life cycle assessment

The environmental impact was evaluated by the LCA analysis approach. The study aimed to evaluate the fuel blend from the perspective of its FU, and energy yield in 30 min of incineration, therefore the fuel amount for each option differs based on its low heating value. As expected, the highest LHV has a pure blend of BP (100%) with decreasing trend to SS (100%). The fuel amount follows the trend of the highest LHV corresponding to the lowest fuel amount. However, based on the fuel composition, the amount of flue gases differs.

This LCA analysis approach was chosen mainly to quantify the emissions based on the ISO 14040/14044 methodology and standards (The Revision of ISO Standards, 2023) which are commonly used nowadays (de et al., 2002). To quantify the environmental impacts to 9 impact categories (Climate change, Fine Particulate Matter Formation Freshwater ecotoxicity, Human toxicity cancer, Human toxicity non-cancer, Marine ecotoxicity, Photochemical Ozone Formation Ecosystems, Terrestrial Acidification, and Terrestrial ecotoxicity), the LCIA method ReCiPe 2016 v1.1 Midpoint (H) was used based on FU of the system. The results for chosen impact categories are shown see Fig. 5.

As shown in Fig. 8, results for the different fuel blend ratios follow correctly the category trend based on the content of the certain element. The LCA analysis approach confirms that the materiál with the highest carbon content, BP 100%, has the highest carbon footprint in the Climate Change [kg CO_2 eq.] impact category (Huijbregts et al., 2017). This fact also proves the study by Výtisk et al. (2023) where the gasification of softwood pellets with lower carbon content than solid refined fuel has a lower impact in the Climate Change category for the process itself (Výtisk et al., 2023). From the ash content point of view, the highest impact in the Fine Particulate Matter Formation category [kg PM 2.5 eq.] is the fuel blend of SS 100%, which has the highest content ash. By reducing this kind of air pollutant there could be a reduction in health issues such as stroke, heart disease, lung cancecer and both chronic and acute respirators diseases including asthma (World Health Organization, 2022). According to EU legislation (Union, 2019) there is a high interest is in mercury production. Although the reduction of SS would be profitable to the environment, it has the highest impact in human toxicity cancer category. That goes hand in hand and follows the trend of the mercury content amount in raw fuel.

Fig. 6 shows also the importance in relating the results to absolute values. Five impact categories with the unit [kg 1,4 DB eq.] shows the exact absolute values, however, the quantification varies in units of orders of magnitude. In addition, the absolute values show better trend steepness. In comparison with the absolute values, the impact category of Climate Change does not vary much. Furthermore, that indicates some of the potential for incineration of SS fuel blend rather than the use of fossil fuels as the SS is considered emission-neutral according to Intergovernmental Panel on Climate Change (Liu et al., 2023b). The study by Hong et. al proved that the co-incineration of sewage sludge presents higher economic benefits (Hong et al., 2013b). The same study says that by decreasing the water content rate of sewage sludge, it can increase the overall environmental burden. That follows the increasing trend for each impact category, except Climate Change since the SS has the highest amount of water in flue gases.

4. Conclusion

Herein, co-incineration of sewage sludge and biomass pellets were developed to determine heat recovery and assess the content of harmful substances in the flue gas as well as the impact of co-incineration on the environment and human from a life cycle assessment perspective. The produced flue gases were analysed using Fourier transform infrared spectroscopy to map the concentration of H_2O, CO, NO_x, NH_3, HCl, SO_2, CH_4, C_2H_6, HF, and O_2. Continuous Mercury Monitoring Systems was developed to determine the concentration of gaseous mercury in the flue gas. BP appeared to be optimal in terms of concentrations, with increasing concentrations of pollutants with increasing SS in the flue gas. In terms of CO2 insertion, the concentration was 4.26–5.61 vol%, with the lowest value

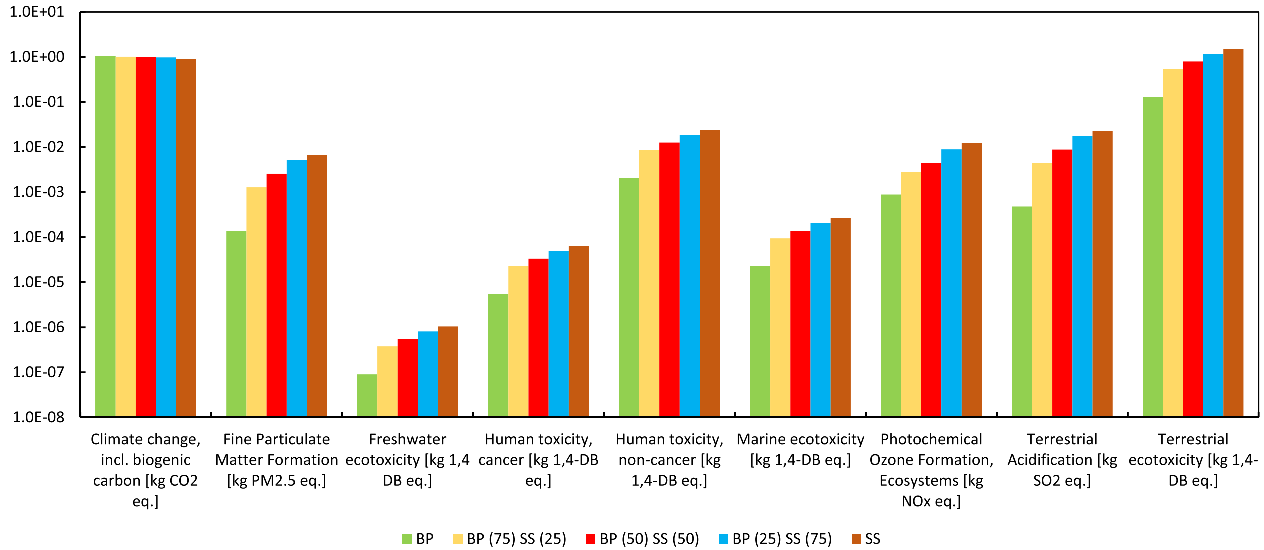

Fig. 5. Quantification of environmental impact in selected impact categories using ReCiPe 2016v 1.1 (H).

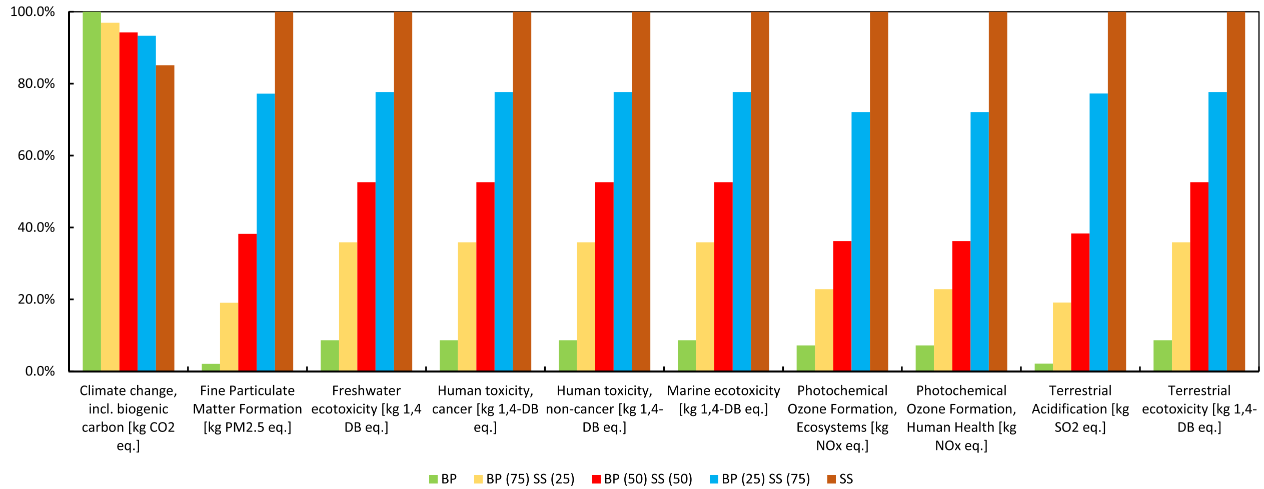

Fig. 6. Absolute values of the results of environmental impact in selected impact categories using ReCiPe 2016v 1.1 (H).

belonging to SS and the highest to BP. The most significant pollutant abundances were NOx 93.3–1156.3, HCl 1.27–55.56, SO_2 12.39–1730.33, and HF 0.15–0.50, all in mg•m_N^{-3}. In terms of gaseous mercury concentrations, the trend was again increasing with the increase SS concentrations, ranging from 8.07 to 83.53 μg•m_N^{-3}. Repeatability of the result is possible only if the same composition of the input fuel, the same air/fuel ratio and the same combustion temperature inside the fluidised combustor are kept. In the case of any change in one or more of these parameters, the production of pollutants may change rapidly, resulting in a change in energy recovery and environmental impact.

Based on emissions quantification and a shift to absolute values, fuel blend ratios can be adjusted to find the ideal mix with the lowest environmental impact or for a specific purpose. The 50% BP / 50% SS fuel blend seems optimal, but considering varying environmental impacts, weighting factors or a representativeness index should also be applied in the blending process.

While sewage sludge is'nt ideal as the primary fuel for large combustion sources, it's effective as a secondary fuel, saving primary fuel costs. The challenge is finding the right blend ratio to maximize cost savings while meeting combustion plant performance and emission limits.

The study's limitations include using a specific sewage source and pellet formation method, leading to potential differences in pollutant concentration, ash content, heating value, and environmental impact when using different sewage treatment plants. Equipment scale for co-incineration also matters. To gain a better understanding, a comprehensive life cycle assessment (LCA) from cradle to grave would provide more information, although obtaining specific data is challenging. Another limitation is that results may differ when using a different type of fluidized bed boiler, like one with a circulating fluidized bed or grate boiler. The composition of the fuel blend also significantly affects energy recovery.

CRediT authorship contribution statement

Jadlovec Marek: Writing – original draft, Investigation, Conceptualization, Visualization **Výtisk Jan:** Writing – original draft, Resources, Investigation **Honus Stanislav:** Writing – review & editing, Supervision, Project administration, Funding acquisition **Pospíšilík Václav:** Data curation, Software **Bassel Nesser:** Data curation, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Appendix A

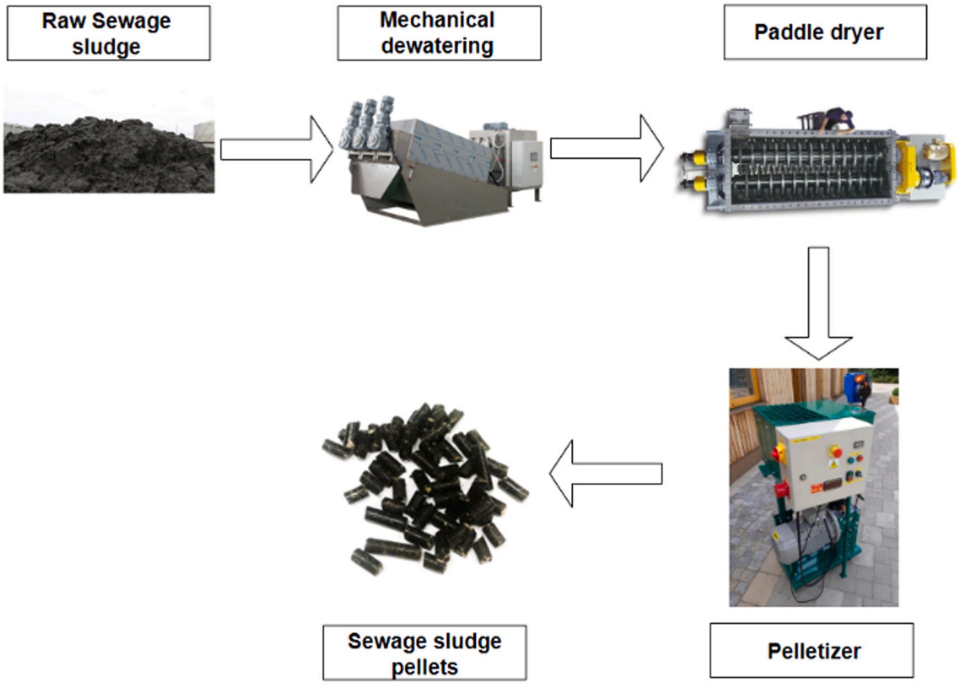

Fig. A1. Process of SS production.

Appendix B

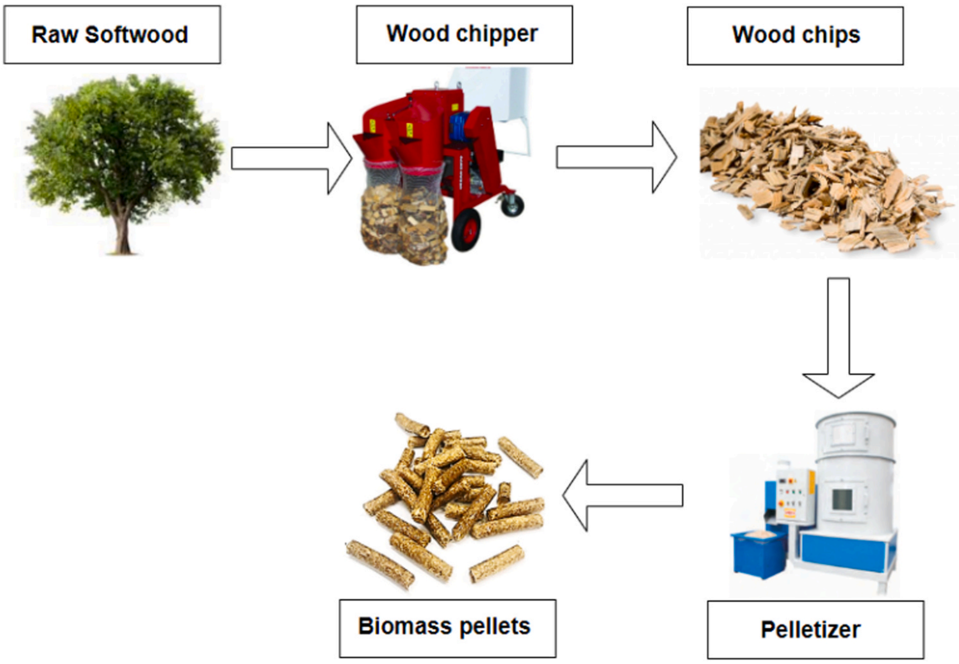

Fig. B1. Process of BP production.

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