Article

Biowaste Treatment and Waste-To-Energy—Environmental Benefits

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Abstract: Biowaste represents a significant fraction of municipal solid waste (MSW). Its separate collection is considered as a useful measure to enhance waste management systems in both the developed and developing world. This paper aims to compare the environmental performance of three market-ready technologies currently used to treat biowaste—biowaste composting, fermentation, and biowaste incineration in waste-to-energy (WtE) plants as a component of residual municipal solid waste (RES). Global warming potential (GWP) was applied as an indicator and burdens related to the operation of facilities and credits obtained through the products were identified. The environmental performance of a WtE plant was investigated in detail using a model, implementing an approach similar to marginal-cost and revenues, which is a concept widely applied in economics. The results show that all of the treatment options offer an environmentally friendly treatment (their net GWP is negative). The environmental performance of a WtE plant is profoundly affected by its mode of its operation, i.e., type of energy exported. The concept producing environmental credits at the highest rate is co-incineration of biowaste in a strictly heat-oriented WtE plant. Anaerobic digestion plants treating biowaste by fermentation produce fewer credits, but approximately twice as more credits as WtE plants with power delivery only.

Keywords: biowaste; waste-to-energy; composting; fermentation; greenhouse gases; global warming potential

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1. Introduction

Biowaste represents a significant component of MSW. In general, biowaste can be considered as a mixture of similar proportions of kitchen and garden waste from households. According to the definition in the EU's Waste Framework Directive (2008) [1], biowaste means "biodegradable garden and park waste, food and kitchen waste from households, restaurants, caterers and retail premises and comparable waste from food processing plants". Thanks to its properties, it is considered to be a renewable and sustainable source for energy production, and therefore its potential should be examined thoroughly.

There are two principal ways of biowaste collection, which also determines biowaste treatment systems. These collection systems are often running in parallel (see Figure 1). First, a dedicated infrastructure for biowaste collection and biowaste treatment is established. Biowaste is source-separated by citizens and handled as a specific stream (See Figure 1 left). Generally, the collection system is diverse, covering a range of options as traditional door-to-door or more sophisticated pneumatic underground system as reported in [2]. This stream ends in composting

plants or digesters and is denoted as SEP-BIO later in the text. However, biowaste is also present in residual municipal waste (RES), and we name this stream RES-BIO. Landfilling is the standard disposal method for RES in developing countries. In contrast, incineration with heat recovery (WtE) is preferred in countries with developed waste management systems. The benefits of WtE were evaluated in [3].
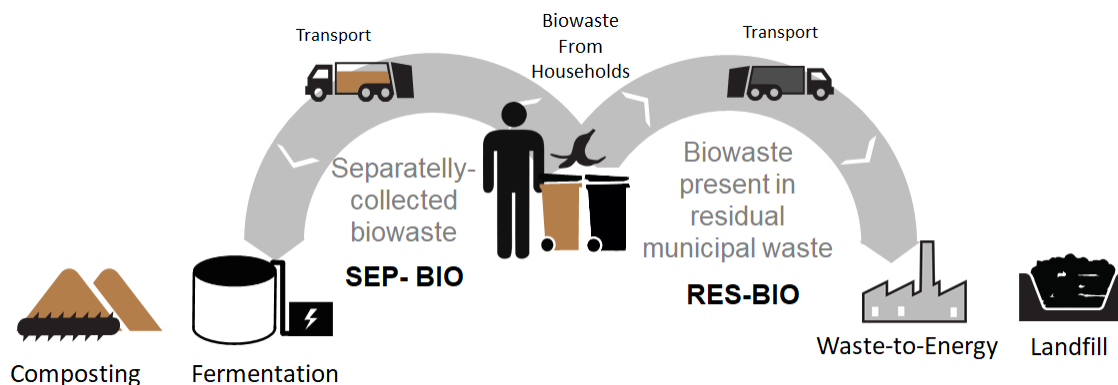

Figure 1. Two sources of biowaste and technologies considered in the analysis.

Depending on the segregation efficiency, the amount of biowaste treated as SEP-BIO or as RES-BIO varies.

The motivation for the investigations presented in this paper is to compare the environmental performance of different routes of waste streams commonly present in RES and treated by WtE. As follows from Figure 1, the main focus is on biowaste. However, the same approach can be applied to other components of RES (discussion on plastics separation and limited recycling options is a hot topic today).

Several studies with comparison of different biowaste treatment methods and biowaste management strategies have been published recently. Papers concerned with biowaste only are shortly reviewed first. Kong et al. [4] performed a comprehensive LCA confirming that the efforts to divert biowaste from landfilling to other ways of treatment (composting and fermentation) bring environmental benefits and reduce (GHG). Ardolino et al. [5] executed an LCA comparing the environmental impacts of different ways of utilisation of biogas produced in an anaerobic digestion plant. The biowaste-to-biomethane scenario, where biogas is upgraded to biomethane and used for transportation, provided higher benefits than traditional biogas treatment by burning in combined heat and power (CHP) unit and subsequent energy production.

LCA studies on residual waste (RES) are widespread. Laurent et al. [6] presented a comprehensive review of LCA studies in the waste management field. Nearly 100 papers dealing with mixed waste were identified. The majority of them is dedicated to RES from households. For example, Arena et al. [7] compared two options of thermal treatment of RES. Dong et al. [8] analysed the environmental performance of gasification and incineration technologies treating RES. The study was based on operational data from existing plants.

However, there are papers also dedicated to biowaste treatment, where biowaste is subject to thermal treatment with air excess. In this case, technologies processing SEP-BIO and RES are analysed together, and biowaste is only a part of the input to the WtE plant. Guereca et al. [9] performed an LCA analysis of biowaste management system for the city of Barcelona. Waste-to-energy was included in the current and proposed scenario. Pubule et al. [10] analysed an optimum solution for biowaste treatment in the Baltic States area. Incineration with and without energy delivery has been included as well. Thomsen et al. [11] carried out a comparative life cycle assessment (LCA) of diverting of the organic fraction of the household waste away from waste-to-energy (WtE) plant to manure-based and sludge-based biogas plants.

The results of the diversion showed a net increase in electricity production but a decrease in heat production. Greenhouse gases emissions (GHG) expressed as global warming potential (GWP) were reduced by 10%. Di Maria et al. [12] conducted a study on the sustainability of biowaste treatment in WtE facilities using a life cycle approach and the cumulative energy demand index. The case study indicated that the treatment of biowaste in WtE plants operated in CHP was more efficient in exploiting the energy content of waste for replacing primary energies than biowaste treatment in anaerobic digestion plants. In addition, the significance of CHP proved to be a critical factor for efficient and effective waste utilization in WtE. In general, the life cycle approach is currently a widely used and favourite tool for research in waste management. Zhou et al. [13] carried out a comprehensive review of LCA tools available for WtE and provided several recommendations for their applications. Mehta et al. [14] successfully applied this principle combined with economic analysis for the assessment of multiple waste management options in Mumbai, India.

Economic performance of a WtE plant treating RES as a mixture of several components was investigated in detail in [15]. In comparison to [16], where the economic model of WtE plant addressed one ton of RES, outcomes of [15] figured out contributions of individual components like paper, plastics, biowaste. A method of the marginal cost was applied. For example, biowaste marginal cost was 160 EUR/t, whereas average of all components, which is also the cost of RES treatment, was 100 EUR/t. For comparison, the cost of plastics was 290 EUR/t. Following the same logic, Ferdan et al. [17] presented an environmental impact of a WtE plant processing RES. The contribution of individual components to the overall performance of WtE was missing. While some LCA studies above focused on biowaste treated in WtE plants, the mechanism of contribution of biowaste treated in a mixture with other components in one processing facility was not sufficiently explained.

In this paper, three ways of ecologically suitable biowaste treatment are discussed—composting, fermentation, and incineration with energy recovery in a WtE plant. The article is concerned with the environmental performance, production of GHG, with a focus on biowaste. This paper aims to compare the environmental impact of the methods mentioned above using the GWP indicator. While GHG production of aerobic and anaerobic treatment of separately collected biowaste are reviewed for comparison reasons, the contribution of biowaste component during thermal treatment of RES in WtE is investigated in detail to cope with uncertainty as mentioned above. An approach inspired by marginal cost [15] is developed, explained, and tested through a case study. Once the contribution of biowaste is known, the influence of the energy-effectiveness of the WtE plant on GHG burdens and credits related to biowaste only is also analysed. Burdens related to the performance of WtE are mainly subject to biowaste content in the input waste [17]. For example, the study [18] analysed fossil-based CO_2 emissions from 10 WtE plants in Austria. Credits are bound with form and amount of energy produced in WtE. Both credits and burdens are profoundly affected by WtE location:

- The amount of utilised heat is firmly bound with the possibility to absorb heat in district heating systems (DHS) or for industrial heating.
- If such a heat sink is not available, less efficient power production is enforced.
- The share of biowaste in RES, technological advancement, and facilities availability will differ; for instance, in developed and developing countries.

Based on the information above, it is suggested that these parameters also influence the feasibility of diverting of biowaste component of RES from WtE treatment to other treatment methods. This paper further explores how the WtE plant operation mode (heat-oriented, power-oriented) influences the environmental performance of the plant. Using the results, the importance of this parameter for the trade-off of the environmental performance of several biowaste treatment methods is evaluated. The published papers concerned with a similar problem (e.g., [11]) did not consider such an aspect in their studies, although the necessity of such evaluation was indicated.

In addition, the detached effect of any component on the environmental performance of WtE plant, if known and described, would be beneficial for sophisticated modelling and simulation of

waste management. Bing et al. [19] highlighted the need for holistic network flow models in waste management. An example of such a model is paper [20], where flows of several municipal fractions are optimised in one complex multiobjective problem. The task demands input data and hardware since it cannot be separated due to WtE processing of all the components of RES.

Section 2 describes the treatment methods—composting, fermentation, and thermal treatment in WtE—considered in this paper, together with the specifications of the chosen treatment plants. It also explains the proposed modelling approach based on marginal change. Section 3 presents the results obtained for each treatment method and a comparison of their environmental performance.

2. Methodology

A generally accepted and suitable indicator to describe the environmental impact of solid waste management systems is the GWP [21]. Even though there are many other assessment categories (respiratory inorganics, terrestrial ecotoxicity, carcinogens), the impact on global warming is the most relevant for assessment is this area [7]. GWP represents the amount of GHG produced or saved in $kg(CO_2)_{eq}$, and the calculated environmental impact can be both positive or negative. In this paper, an inventory related to subsequent GWP evaluation is performed during the calculations of the WtE case. In the case of other treatment methods—composting and fermentation—an LCA inventory was used for evaluation and follow-up trade-off.

2.1. Goal and Scope

The goal of this paper is to compare the environmental impact of biowaste treatment in a composting plant, an anaerobic digestion plant, and a WtE plant using the GWP indicator. Biowaste treatment in WtE is investigated in detail using a small case study. Correctly, an energy production-related analysis is used to examine the influence of the WtE plant mode of operation on environmental performance. The following text describes the investigated treatment methods and lists the specifications of the chosen treatment facilities.

2.2. Fermentation and Composting Processes

2.2.1. Description

Composting is a naturally occurring process of aerobic breakdown of natural matter by microorganisms. Reyes-Torres et al. [22] carried out a systematic review of green waste composting. The raw input material for composting is biowaste, as defined earlier. The process itself is relatively simple. However, the composting plant has to be controlled and operated well. In another case, there is an increased risk of excess odour, and greenhouse emissions production, low quality of the output products, and the process itself can be considerably slower [22]. Details of the composting process and technology used can be found in [23] and are not described in this paper in detail.

Fermentation, when compared with composting, occurs without access to oxygen—it is an anaerobic process. It is also often described as the anaerobic digestion process. The input material for this treatment process is any biologically degradable compound called the substrate. The output products are two—digestate, which is usually present in liquid form; and biogas with its two main components, methane and carbon dioxide. The process of anaerobic digestion is a complex of chemical reactions and its description and other details on fermentation processes are given in, for instance, in [12]. Fan et al. [24] analysed the carbon emission footprint in pre-and post-treating MSW in fermentation processes.

An LCA analysis is used to determine GHG production from these two processes. As the reference unit, the disposal of one ton of separately collected biowaste (SEP-BIO) is set.

The following processes are to be considered within the system boundaries (Figure 2): the specific waste treatment process (fermentation, composting) itself, including the further treatment of intermediates from the disposal process and all linked material and energy, flows related to the

need for materials and supplies. In addition, the emissions from the collection and transport of the inputs (SEP-BIO) are considered. Additional benefits such as energy and secondary materials (e.g., fertilisers, organic matter) result from the disposal processes. Corresponding amounts of energy or products/articles do not need to be produced conventionally from primary processes. The environmental impacts that would be associated with the conventional manufacturing/production of each of the substituted primary raw material are thus "saved" or "avoided". The provision and maintenance of infrastructure (construction, service and repair of buildings, machine, industrial facilities) are not considered, as they are not expected to have a decisive influence.
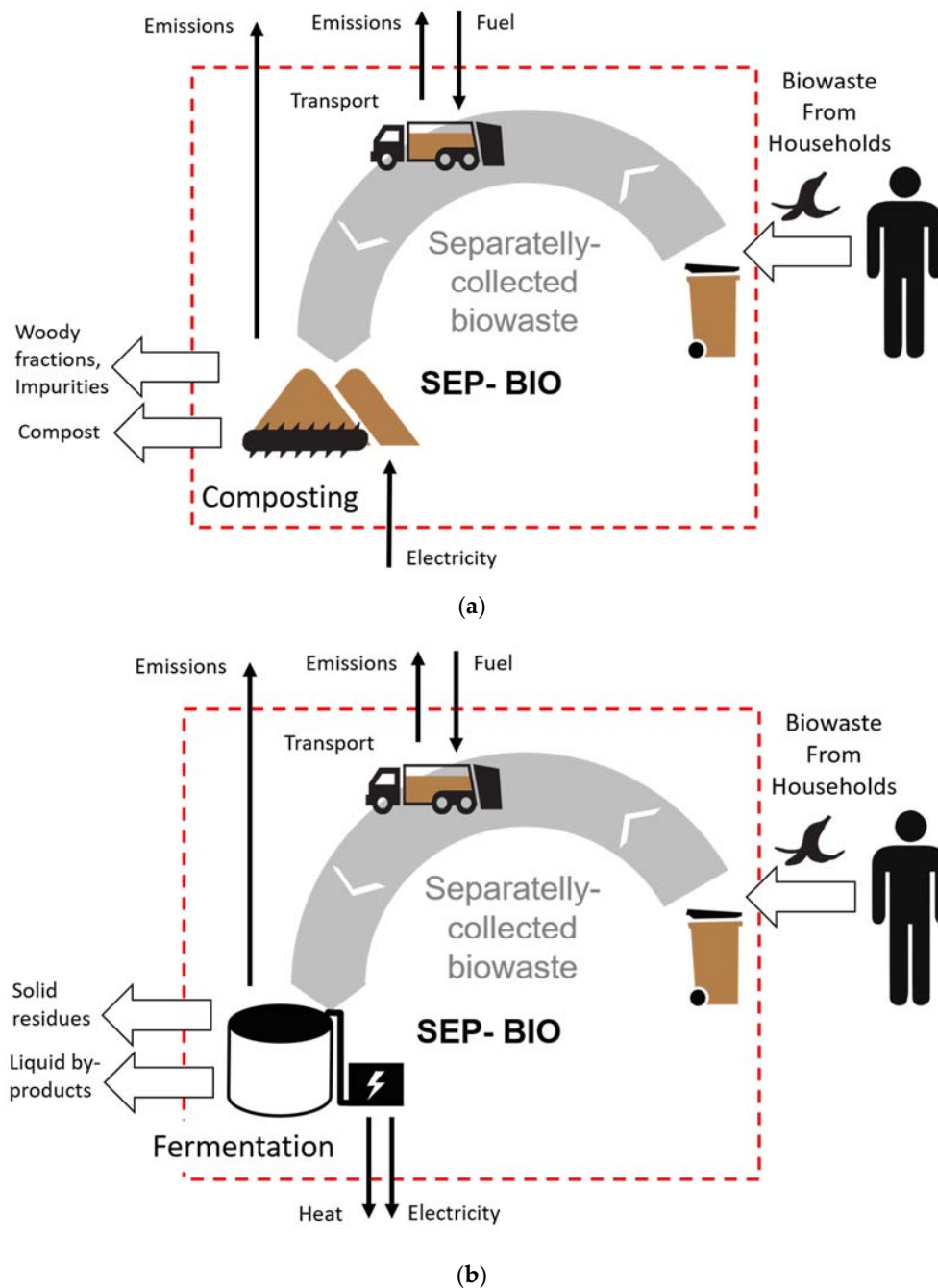

(a)

(b)

Figure 2. System boundaries for separately collected biowaste (SEP-BIO) treatment routes: (**a**) composting; (**b**) fermentation.

2.2.2. Specifications

The collection of biowaste for both treatment methods is realised by door-to-door collection. The GWP value of 1.25 $kg(CO_2)_{eq.}t_{waste}^{-1}km^{-1}$ was considered for a collection vehicle [25] and value of 0.088 $kg(CO_2)_{eq.}t_{waste}^{-1}km^{-1}$ for a EURO5 truck [26] used in transport. The distance driven by the collection vehicle was estimated as 10 km, and the transport distance to a treatment facility was set to 50 km for both cases.

In the case of the composting plant, it is assumed that 10% of composting plants are open and 90% of the plants are closed. Any impurities are separated, and the plants produce ready-made compost only. The amount of compost yield is 440 kg/t of biowaste. As for the anaerobic digestion plant, a continuous dry fermentation with composting of solid fermentation residues was supposed. The biogas yield is assumed with 100 m_N^3/t of biowaste.

2.3. WtE Process

Waste can also be effectively treated in WtE facilities. Typically, large WtE plants thermally treat RES by incineration and the released heat is recovered using CHP production. According to [27], approximately 27% of all MSW generated in EU28 in 2014 was processed by incineration with energy recovery. In case of WtE, which is of the most importance in this paper, positive values of GWP are so-called GWP burdens, and they are the result of production of GHG and release of their emissions into the air.

On the other hand, negative values are GWP credits, and they characterise decrease in global production of GHG, thanks to the replacement of fossil fuels and primary raw materials. GWP calculation method for WtE plant is based on the work [15], where the author introduced inventory analysis. Here, GHG production is calculated similarly following the same assumptions and data.

To operate the WtE facility effectively and sustainably, it is essential to pay attention to a range of conditions—one of them is also the input waste composition. Table A1 in Appendix A lists the RES composition used in the calculations in this paper. Biowaste share for particular RES composition is relatively high (28.9%) when compared to other components. Waste composition significance and its effect on the efficiency and operating conditions of the plant was described in [15]. Biowaste is characterised by zero content of fossil-based carbon. Therefore, its incineration is free of GWP burdens and generates GWP credits as replacement of traditional fossil-based resources. On the other side, its calorific value is only 4.6 $GJ.t^{-1}$, which is quite low when compared, e.g., with plastics.

Modelling Approach

In the following text, the calculation of GWP of the WtE plant is described in detail. All the calculations were done using a computational model designed in Microsoft Excel. The calculation procedure itself consisted of several steps. To be able to assess GWP credits, the amount of energy recovered from the treatment process had to be determined. In this case, a techno-economic model of a WtE (TE model) thoroughly described in [17] was used and is briefly discussed further in the text. The values of GWP burdens were determined from the basic combustion equations and the amount of the products (CO_2). Both of this information is highly influenced by the waste composition and its properties such as the content of fossil-based carbon and calorific value of the waste., A specialised tool called JUSTINE, available at the workplace of the authors, was used to satisfy the requirement for high-quality data estimation. This tool is further described in [28]. After gathering both GWP credits and GWP burdens, a simple balance was performed and the net GWP obtained by the approach is summarised in [17]. Using this method, the resulting GWP of thermal treatment of RES without distinguishing its components can be readily determined. However, the paper aims to determine the GWP of biowaste component of RES.

To obtain such information, a concept of marginal change was proposed in this contribution. This concept is widely applied in economics. We then speak about marginal cost. The marginal cost concept

has been employed in the field of waste management in a complex [15], where the impact of RES components on WTE plant economy has been investigated. However, the authors are not aware of any application of this concept for GWP analysis.

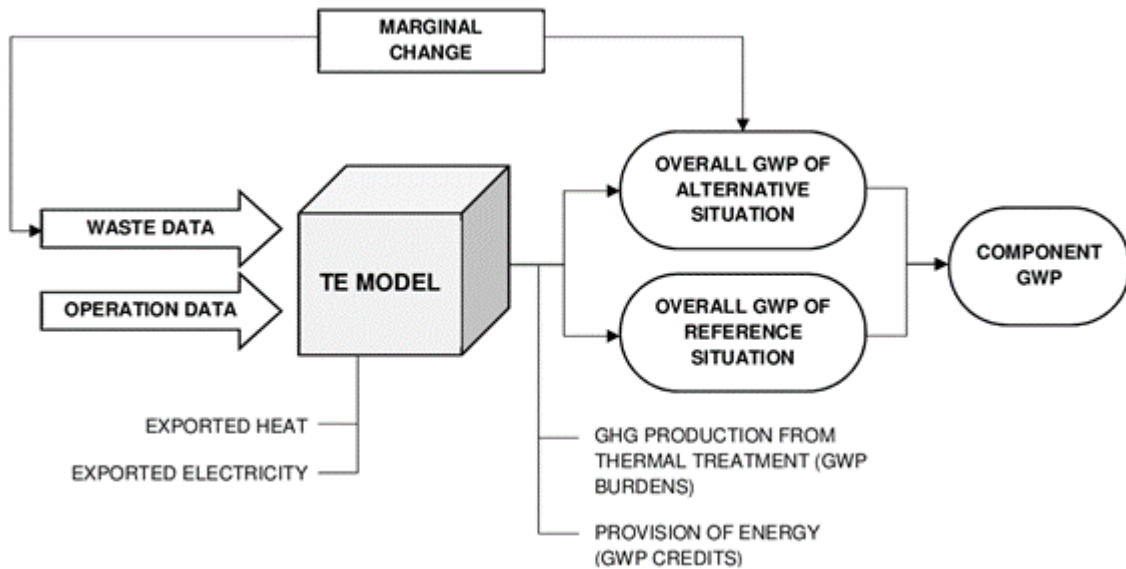Figure 3 hows the steps required to apply such an approach in this case:

Figure 3. Calculation concept using the marginal change approach to evaluate GWP related to processing components of residual waste (RES) in waste-to-energy (WtE).

i　Firstly, the overall GWP for the whole amount of RES processed in WtE per year is calculated according to the procedure described in the previous paragraph, and according to [17], the resulting GWP is denoted as reference one and corresponds to the current composition of RES, $GWP_{REFERENCE}$.

ii　Secondly, the marginal change of the input RES is defined, and its effects on results are assessed. The marginal change is the diversion of a specific amount of one of the waste components from the original composition of RES—in this case, biowaste. This change is denoted as $m_{MARGINAL}$, and it expresses the biowaste removed from the input RES, i.e., the amount of input RES processed in WTE per year is decreased. The calculation procedure in the step (i.) is then repeated. The overall balance of the WTE plant is slightly modified, and the calculations lead to a new GWP value, which is called $GWP_{ALTERNATIVE}$. This value, therefore, represents the overall GWP for the whole amount of RES processed in WTE per year decreased by $m_{MARGINAL}$.

iii　Finally, based on the assumption that the marginal change is exclusively related to one of the RES components, the GWP corresponding to the specific component—biowaste, in this case—can be computed. Such value is denoted as GWP_{COMP} or GWP_{BIO}, and results from a simple equation:

$$GWP_{COMP} = GWP_{BIO} = \frac{GWP_{REFERENCE} - GWP_{ALTERNATIVE}}{m_{MARGINAL}}. \tag{1}$$

Such a component-specific GWP calculation is a base for WtE process evaluation, according to system boundaries displayed in Figure 4.
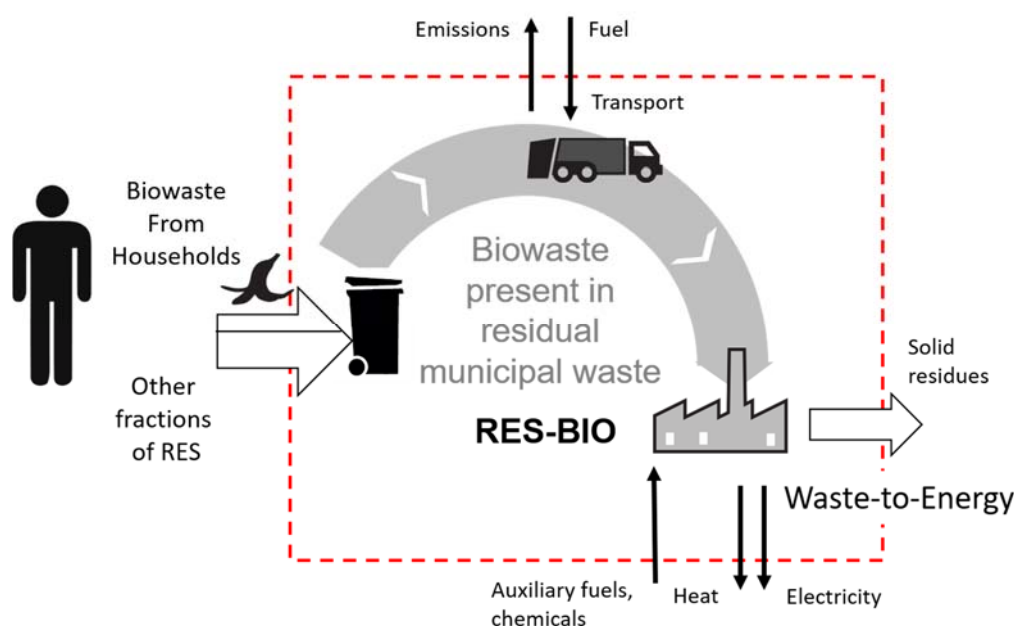
Figure 4. System boundaries for biowaste treated with other components of residual waste (RES-BIO) in WtE plants.

The case study considered in this paper is adjusted to suit current European conditions and is mainly focused on the Czech Republic. The input waste data, technological advancement, infrastructure availability (e.g., heat distribution network), and WtE plant specifications were chosen accordingly:

- RES composition is listed in Table A1 in Appendix A and was estimated specifically for The Czech Republic using tool JUSTINE [28].
- The fuel mix for power and heat industry in the Czech Republic used for GWP calculations is given in Table A2 in Appendix A.
- The WtE plant capacity was selected as 100 kt of RES per year. Technological specifications are according to [17]. The released heat is utilised in a heat recovery steam generator (HRSG) to generate superheated steam at 4 MPa and 400 °C. This steam is further used in cogeneration by the employment of extraction condensing steam turbine. In such type of turbine, the ratio between heat and power can be freely adjusted. Heat is exported in the form of hot water and supplied into the district heating system. The exported electricity is sold to the national electricity grid. The operational hours of the plant are stated as 8000 h/y.
- The amount of biowaste diversion is 5%, which at plant capacity yields approximately 1.45 kt of biowaste per year.
- The processes considered within the system boundaries are of the same nature as given for composting and fermentation.

3. Results

The results obtained by both LCA inventory and GWP inventory are presented below.

3.1. Composting

The environmental impact of biowaste treatment by composting is summarised in Figure 5. The overall value of GWP burdens of biowaste composting is 94.9 kg$(CO_2)_{eq}$.t$_{waste}$$^{-1}$ consisting from environmental burdens from collection and transport (16.9 kg$(CO_2)_{eq}$.t$_{waste}$$^{-1}$) and from the treatment itself (78 kg$(CO_2)_{eq}$.t$_{waste}$$^{-1}$). On the other side, a positive effect—GWP credits with a value of −152 kg$(CO_2)_{eq}$.t$_{waste}$$^{-1}$—result mainly from the substitution of primary resources such as fertilisers

or substrates. The net GWP value of biowaste treatment, including transport and collection, is equal to $-57.1 \ kg(CO_2)_{eq}.t_{waste}^{-1}$.
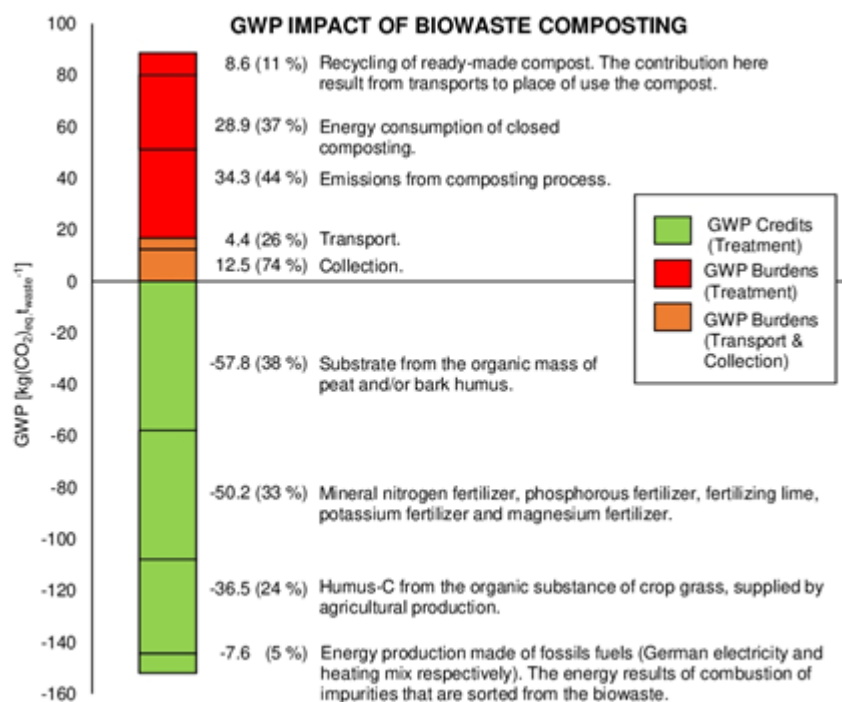

Figure 5. The overview of the environmental impact of biowaste composting expressed using GWP via SEP-BIO.

3.2. Fermentation

Figure 6 shows the environmental impacts of a biowaste recycling process via fermentation. In this case, the net GWP result of this process, including biowaste transport and collection, is reduced by 206.1 $kg(CO_2)_{eq}.t_{waste}^{-1}$. GWP credits are mainly obtained by the substitution of primary resources as well as from the saved energy and yield $-315 \ kg(CO_2)_{eq}.t_{waste}^{-1}$. On the contrary, burdens from the fermentation process only are nearly similar to that of composting with a value of 92 $kg(CO_2)_{eq}.t_{waste}^{-1}$. Burdens from collection and transport are the same as in the previous case, thus 16.9 $kg(CO_2)_{eq}.t_{waste}$.

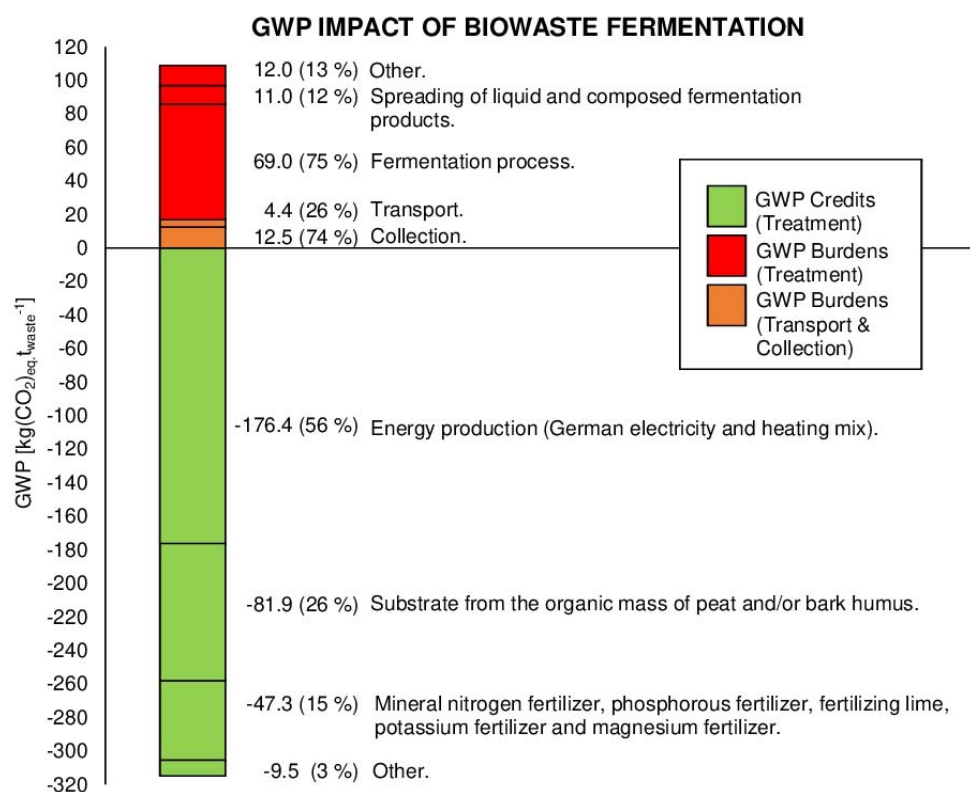**GWP IMPACT OF BIOWASTE FERMENTATION**

Figure 6. An overview of the environmental impact of biowaste fermentation expressed using GWP, via SEP-BIO.

3.3. Incineration with Energy Recovery

While composting and fermentation processes use SEP-BIO (separation is done by producers/citizens), WtE handles biowaste present in residual waste (RES-BIO).

Figure 7 shows the resulting GWP of biowaste treatment in the WtE plant as a function of percentage utilisation of heat production. The horizontal axis displays the ratio between heat and power production during cogeneration. If the value is equal to 100%, the plant is heat-oriented, and it maximises the export of thermal energy into the network still working as a combined heat and power plant. Maximum steam goes through the extraction valve of the turbine. On the other hand, 0% indicates a strictly power-oriented plant, where no heat for export is produced, and electricity generation is maximised. All the steam flows through the condensing stage of the turbine.

It can be observed that the overall environmental effect of biowaste utilisation is in this case, always positive. This can be explained as follows: The values of GWP burdens are of the same value for both cases—before and after biowaste diversion. That is because biowaste component of RES does not contain any fossil-based carbon and therefore does not participate in GHG production during oxidisation of waste. On the other hand, GWP credits are related to BIO share. When an amount of biowaste with a heating value of approximately 4.6 $GJ.t^{-1}$ is removed, both exported heat and electricity decrease and therefore fewer credits from fossil fuels substitution are obtained. The highest overall GWP value of -272 $kg(CO_2)_{eq}.t_{waste}^{-1}$ is achieved when all the available energy is exported as heat. If all the energy is exported as electricity, the GWP credits are more than twice lower at -115 $kg(CO_2)_{eq}.t_{waste}^{-1}$. Please note that although the result of the calculation of Equation (1) is positive, a positive environmental impact of biowaste treatment in WTE is desired, and therefore, the value is considered to be negative. The values of both GWP burdens and credits produced per year are summarised in Table 1 for strictly heat-oriented and power-oriented plants.
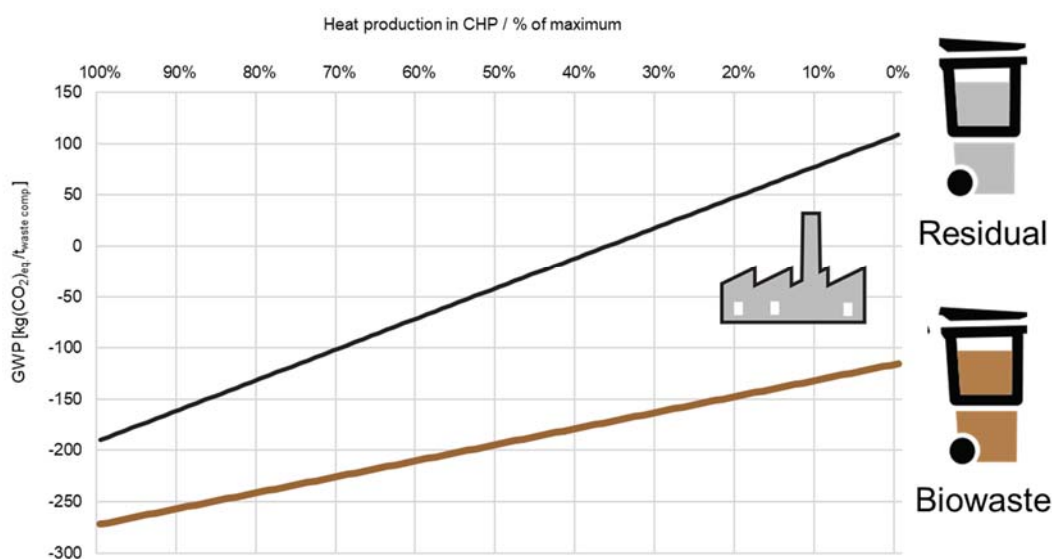
Figure 7. GWP as a function of percentage utilization of heat produced in WtE—the total balance for RES and contribution of its component biowaste (RES-BIO).

Table 1. Global warming potential (GWP) of residual waste (RES) in waste-to-energy (WtE) before and after biowaste component diversion.

Source	GWP Impact	100% Heat Prod. in CHP GWP $[kt(CO_2)_{eq}.y^{-1}]$		0% Heat Prod. in CHP GWP $[kt(CO_2)_{eq}.y^{-1}]$	
		Before	After	Before	After
GHG from waste incineration	burden	37.140	37.140	37.140	37.140
Heat export	Credit	−49.570	−49.192	0.000	0.000
Electricity export	Credit	−6.671	−6.656	−26.584	−26.418
Net result	overall	−19.101	−18.708	10.556	10.723

　　GWP is sensitive to waste composition, WtE plant efficiency, and fuel mix for power. The result for electricity-oriented operations is similar to other works published. For example, total emissions of CO2, eq. with a positive sign (burdens prevail over credits) for WtE operated as a power plant have been reported in [7]. On the other hand, previous investigations into WtE plants with a high share of heat delivery are missing, since only a few countries and regions have district heating systems with sufficient demand on heat, compared to required WtE capacity. The future potential for centralised systems of heat delivery in Europe has been analysed by the Heat Roadmap Europe initiative (see [29]).

　　The result of GWP of biowaste can also be compared with GWP of RES, considering it as a mixture of various components. GWP of RES treatment in the WtE plant as a function of percentage utilisation of heat production is also shown in Figure 2. Although the lower heating value of biowaste is low, biowaste is a component of RES, which offers significant credits for WtE operation and RES incineration.

　　The standard operating mode for a typical WTE plant in the Czech Republic, considering the seasonal fluctuations of heat demand, would be approximately 75% heat production in CHP. The structure of GWP burdens and credits of biowaste processing in a WtE plant operating in this mode is shown in Figure 8.
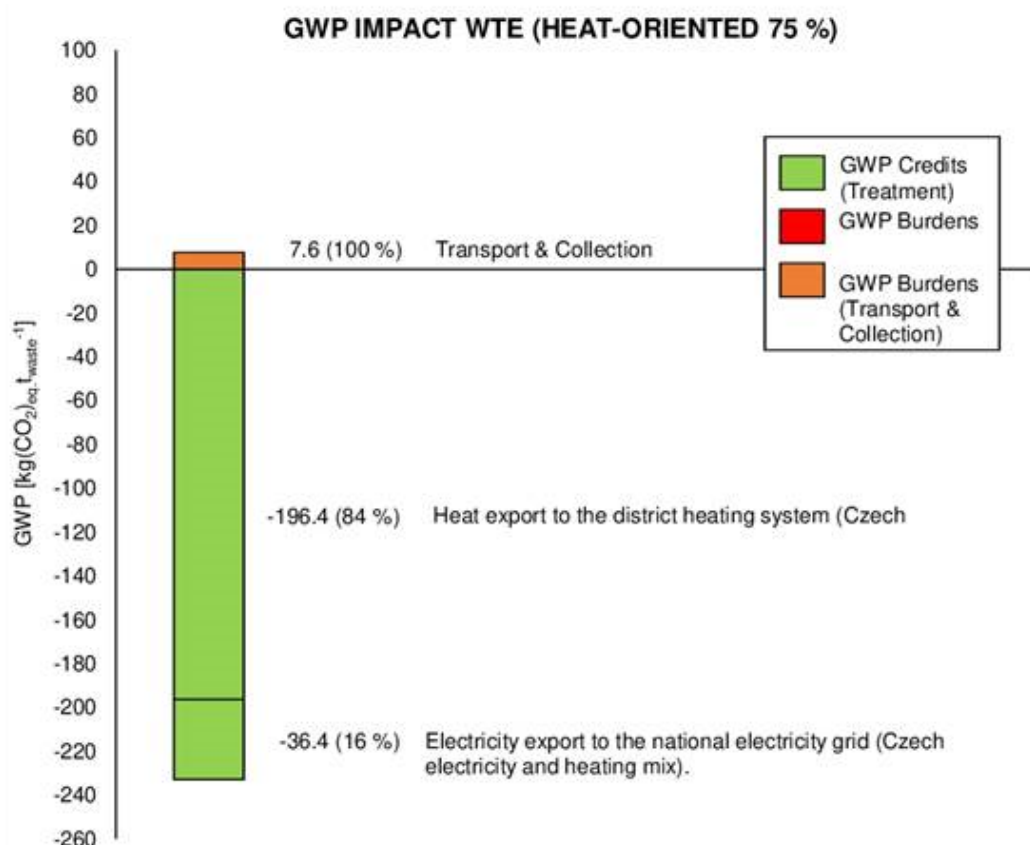
Figure 8. GWP impact of biowaste (SEP-BIO) incineration in WtE with heat production with CHP 75% of the maximum.

The values in this figure were obtained by applying Equation (1); therefore, they express the difference between the reference and alternative situation. In this case, the net value of GWP is equal to -225.2 kg$(CO_2)_{eq.}$t$_{waste}^{-1}$. The GWP burdens are close to zero because biowaste component of RES does not contain any fossil-based carbon and therefore no additional GHG is produced. The GWP credits resulting from heat production are equal to -196.4 kg$(CO_2)_{eq.}$t$_{waste}^{-1}$ and from power production $-36,4$ kg$(CO_2)_{eq.}$t$_{waste}^{-1}$. The GWP burdens resulting from transport are estimated at 7.6 kg$(CO_2)_{eq.}$t$_{waste}^{-1}$.

3.4. Biowaste Treatment Methods Comparison and Discussion

Based on the data above, the environmental performance of the three previously discussed ways of biowaste treatment can be compared in Figure 9.

Each of the net results of individual treatment method is negative, which means all of the abovementioned methods are beneficial from an environmental point of view, thus saving GHG.

The least credits are obtained by biowaste composting, which is also considered as a less investment-demanding method. The values of GWP for treatment in anaerobic digestion plants and WtE plants are comparable—depending on the operational mode of WtE. If the WtE plant is mostly heat-oriented, its environmental performance is more favourable than treatment by fermentation. However, if the WtE plant is strictly power-oriented, it generates fewer GWP credits than an anaerobic digestion plant.

There is a worldwide trend towards environmentally friendly waste management, with an effort to reduce the consumption of primary raw materials. This trend is known as the circular economy, and the EU, in particular, is very active in supporting circularity principles in waste management.

One of the significant achievements of EU legislation is the gradual implementation of the circular economy package. Since an increase in the share of municipal waste recovered materially to 65% by 2035 is obligatory for EU member states, WtE appears as a less important part of the system. Instead, separate collection of various fractions of MSW is stipulated. Reduction of RES is anticipated at the same time. In this respect, the separation of biowaste is becoming more and more popular and common. The two basic treatment methods of separated biowaste are composting and fermentation. The easiest and at the moment, the most widespread method, is composting. When compared with fermentation, it has fewer requirements for technical equipment and is less demanding on both capital and operational costs. From an environmental point of view, based on the obtained data, composting is a less-favourable method of biowaste treatment than fermentation, as worse GWP results suggest. The separation of biowaste as a single component is connected with the requirement for additional infrastructure such as specialised biowaste containers and collection, which increases the price. A collection of biowaste as a component of RES and its subsequent incineration with energy recovery in WtE plant can help avoid the extra expense. The simple GWP evaluation and related energy production-related analysis showed that the environmental impact of this method heavily depends on the operational mode of the plant. Based on the calculations performed, strictly power-operated WtE plants using normal steam parameters perform environmentally worse than anaerobic digestion plants. However, environmental performance improves with increased heat production in CHP. The more waste heat is used to export heat, the better results are obtained. The operational mode, CHP, proved to be the decisive parameter for the environmental performance of the WtE plant.

Considering these results, biowaste treatment as a component of RES incinerated in WtE showed the most significant environmental potential and should not be excluded from the range of choices of biowaste treatment methods during waste management planning. The results of this small case study correspond with the results in [12] with WtE proving to be more environmentally-friendly under certain conditions and at the current state of technological development. While composting and fermentation methods are currently more favoured (recycling) than waste incineration with energy recovery for biowaste streams, the contribution of WtE is also significant when heat is positively utilised.

The presented result is subject to boundary conditions. The figures presented are based on data for the Czech Republic. The most important aspect is the composition of RES and energy mix, which could be country-specific (see Appendix A). The extent of variation is in accordance with previous studies, where comprehensive sensitivity analysis was done (e.g., in [8]).

The need for sustainable energy production through MSW treatment is also highlighted in the study [30]. However, it should be pointed out that material products from composting and fermentation have the potential to provide nutrients (especially phosphorus) and organic matter to supply the soil. This additional environmental benefit with a view to the conservation of resources cannot be provided by WtE use of biowaste. A more detailed study further exploring both environmental and economic aspects of biowaste treatment in chosen plants should be conducted and then reviewed. The research presented in this paper confirmed that the potential of biowaste treatment can be environmentally beneficial and must be further explored.

The results of the calculations and, especially the methodology of marginal change, can also be further used in more detailed stages of waste management planning, e.g., when solving so-called reverse logistic problems, which are tools used for the detailed description of waste streams and complex waste management systems planning [19]. The methodology could be applied to other components of RES, which can provide input data for the reverse model, where components of RES are considered in detached problems. For example, plastics treatment chains are hot candidates for further investigation and optimisation due to recent unfavourable changes in the secondary material market.
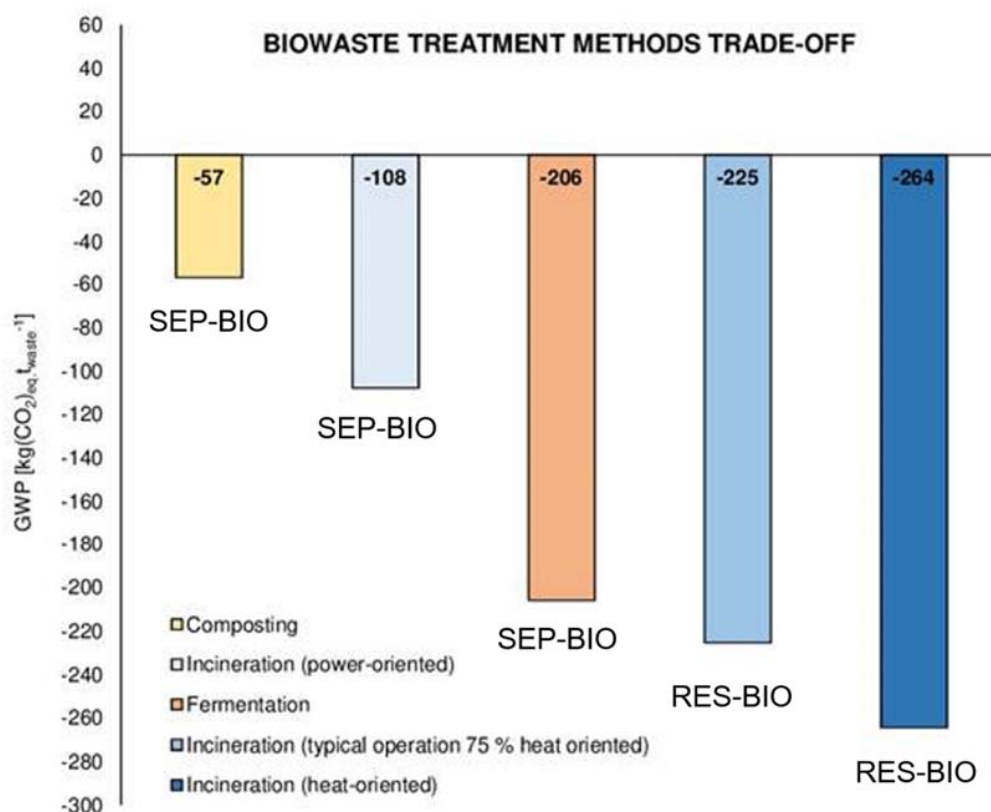
Figure 9. Biowaste treatment methods' comparison, SEP-BIO and RES-BIO alternatives.

4. Conclusions

Biowaste separate collection and its subsequent treatment by composting or fermentation are considered a sustainable way of handling this waste stream. First, an inventory of GHG for a composting process and fermentation process was carried out. The modelled cases suited current European conditions and are mainly focused on the Czech Republic's conditions. The net GWP value of biowaste treatment by composting, including transport and collection, was equal to -57.1 $kg(CO_2)_{eq}.t_{waste}^{-1}$. Positive effect resulting in GWP credits, which result mainly from the substitution of primary resources such as fertilisers or substrates, are burdens from the collection, transport, and treatment itself. Much positive effect can be achieved through fermentation, where net GWP of -206.1 $kg(CO_2)_{eq}.t_{waste}^{-1}$ can be achieved. In comparison with composting and fermentation, WtE processes biowaste present in residual waste. Therefore, the effect of biowaste incineration as a component of residual MSW was investigated next. A simulation model based on a marginal change concept was proposed for this purpose. Since net GHG emissions (burdens plus credits) are, in the case of WtE, dependent on heat utilisation rate (district heating systems), the primary goal of the case study was to carry out an energy production-related analysis. In the case of high heat delivery (75% of the thermal output of the boiler), the effect is comparable with the impact of fermentation/composting. In the case of missing heat demand (electricity generation), separate collection and fermentation is preferred.

Appendix A

The share of biowaste on the total composition of RES can vary greatly depending on different factors such as economic and social development of the country, legislation, or geographical location. It has to be highlighted that accurate and reliable data on waste composition is a critical input for environmental assessment calculations [31]. Consequently, a great deal of attention has to be paid when assessing these data. In this paper, the composition of RES for the Czech Republic obtained using tool JUSTINE was used. Such values would also be typical for other similarly developed countries in Europe.

Table A1. RES composition for the Czech Republic obtained using tool JUSTINE [28] for 2016.

Component	RES Composition [%]	Fossil-Derived Carbon [kgt^{-1}]	Calorific Value [GJ.t^{-1}]
Metals	2.68	0.0	0.0
Glass	5.12	0.0	0.0
Paper	7.78	0.0	13.0
Composite packaging	2.99	219.0	18.0
Plastic	9.32	0.0	34.0
Biowaste	28.92	0.0	4.6
Textile	5.72	172.0	15.0
Mineral waste	3.32	19.0	0.0
Hazardous waste	0.62	416.0	17.0
Electronic waste	0.42	441.0	22.9
Other combustibles	14.38	45.0	4.4
Fine fraction (under 40 mm)	21.73	46.0	5.1
Total	100	101.3	8.46

Table A2. The fuel mix for the power and heat industry in the Czech Republic (Slivka, 2011) [32].

	Power			Heat		
	Share	**CO$_2$ Production**			**Share**	**CO$_2$ Production**
Reference	[%]	[kg(CO$_2$)GJ^{-1} of Produced Power]	**Reference**		[%]	[kg(CO$_2$)/GJ^{-1} of Produced Heat]
Coal	51	337	Coal		59	112
Natural gas	8	187	Natural gas		24	62
Nuclear	30	0	Other gases		4	73
Water	1	0	Renewables		9	0
Solar	3	0	Heating oil		4	85
Wind	1	0				
Biomass	6	0				
Total	100	187	Total			88

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