Chapter

Opportunities of Circular Economy in a Complex System of Woody Biomass and Municipal Sewage Plants

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Abstract

In this chapter, we present the opportunities and general importance of woody biomass production (forests and short-rotation coppices) and waste management in a common system. Wastewater and different forms of sewage sludge, as energy- and nutrient-rich materials, can contribute to reaching resource efficiency, savings in energy, and reduction of CO_2 emissions. Within certain limits, these woody plantations are suitable options for the environmentally sound disposal of wastewater and/or sewage sludge; in addition, they can facilitate the realization of full or partial energy self-sufficiency of the wastewater plant through bioenergy production. Focusing on circular economy, we introduce the aspects of the treatment process and the sizing issues regarding the municipal wastewater treatment and the woody biomass in a complex system. Based on a specific case study, approximately 826 ha of short-rotation coppices (with a 2-year rotation) are required for the disposal of sewage sludge generated by a 250,000 population equivalent wastewater treatment plant. If we look at the self-sufficiency of its energy output, 120–150 ha of short-rotation coppices may be adequate. This complex system can replace the emissions of around 5650 t of CO_2 through electricity generation alone and another 1490 t of CO_2 by utilizing the waste heat.

Keywords: circular economy, complex system, sludge management, self-sufficiency, short-rotation coppices

1. Introduction

In this chapter, we introduce the possibilities for connecting woody biomass production and municipal-level wastewater management. Both topics are usually examined on their own, but in our opinion, their application in a common system can implement the concept of a circular economy in a very promising way as well as facilitate the implementation of environment protection goals and tasks [e.g., energy efficiency, reduction of greenhouse gas (GHG) emissions, and waste management].

Circular economy is the concept in which products, i.e., materials (or raw materials and feedstock) participate in the economic cycle for as long as possible, and in which waste is used as a secondary raw material that can be recycled and reused.

The focus is on minimizing losses, reusing, and recycling [1]. As a key factor, lack of resources will primarily result in modern forms of waste management [2]. One of the possibilities is to combine wastewater treatment with woody biomass production and to utilize (even for multiple purposes) the resulting outputs.

Wastewater and different forms of sewage sludge (especially sewage sludge compost), as energy- and nutrient-rich materials, can contribute to reaching resource efficiency, energy savings, and CO_2 reductions. Within certain limits, woody plantations are suitable options for the environmentally sound disposal of wastewater and/or sewage sludge; in addition, they can facilitate the realization of full or partial energy self-sufficiency of the wastewater plant through bioenergy production, or sometimes even extra energy can be generated.

We think there is an observable tendency that, all around the world, more and more people are moving to cities and producing an increasing amount of waste, a significant (and difficult to handle) part of which is generated in liquid form. In contrast to smaller settlements, industrial plants operating in urban environments also emit large amounts of organic matter, the treatment of which together with municipal wastewater must be solved, preferably in an automated and cost-effective way. During this process, renewable energy can also be produced by anaerobic digestion. In addition, the utilization of digested material (sludge) with high macro- and microelement content for nutrient management presents a serious problem to be solved, especially in the case of industrial wastewater. In contrast to arable land used for food crops, high levels of inorganic matter and, in some cases, relatively high levels of heavy metals do not pose a food safety threat in the case of short-rotation coppices (SRCs).

It should be noted that the placement of sewage sludge on agricultural land is problematic due to the reluctance of producers, even if the legal environment of the given country allows the use of sewage sludge for agricultural purposes, not to mention the high cost of placing high moisture sludge.

Nowadays, a wide range of technologies for the purification and treatment of generated wastewater are recognized and applied, ranging from extensive drying and the traditional, most widely used (activated sludge) process to innovative, novel, and environmentally sound wastewater treatment solutions.

Here, we first briefly make plain the most important relevant characteristics of SRC and afterward focus on wastewater management issues and the connection between wastewater treatment plants (WWTPs) and SRCs. We continue with introducing a case study to make the sizing problem clear, and finally, we will demonstrate with some international examples that this topic is no longer in the distant future but is now active in the present.

2. The significance of forests and short-rotation coppices

Forests represent an irreplaceable national treasure and a form of land use that provides financial security and intellectual refreshment. Truth be told, they are also fundamental to the protection of our environment. From the cradle to the grave, trees accompany us. Many forms of their benefits cannot be expressed in money, yet they are irreplaceable. The ideological value of forests is incalculable. Long-rotation forests have a wide range of social functions but are no longer able to fully meet the increased need of biomass for energy.

The most important economic characteristics of long-rotation forests can be summarized by the fact that, due to their long production cycle, the significant planting costs are only recovered much later, making market price changes impossible to follow. During their lifetime, only small revenues are expected from clearing and thinning. In average, more than 50% of air-dried wood is carbon, since trees are able to capture and store significant amounts of carbon [3]. These forests also play an important role in providing protection against winds and floods, in addition to producing oxygen, shade, and a humid microclimate. For example, in Hungary, the utilization of the floodplains for forestry purposes is complicated by the fact that these areas are divided in terms of ownership. Some may be state-owned and managed by the authority of water resources and forestry, as well as national parks, while some of them are privately owned. Game management and hunting offer new land use and income opportunities for foresters and producers leaving agriculture. Wild animal parks and public events can also function as an ancillary activity of agriculture, but they can also be reasonably connected with tourism (e.g., rural and ecotourism) and various rural development programs. However, the role of traditional logging in rural employment cannot be neglected either.

The functions of forests described in the previous section are essential, but their energy role is just as crucial, becoming ever more important. Of the different renewable energy sources, mankind has been using biomass for energy purposes for the longest time, and even today, firewood is the most important energy source for about two billion people [4]. An important aspect of meeting energy needs is that the wood should be of uniform quality, produced in as small an area as possible with relatively high biomass yields at the lowest possible cost—all of which are typical of short-rotation coppices. Another important aspect is to be suitable for use under automated conditions, that is, in large-scale central heating or cogeneration plants. SRCs are probably the best way to relieve the burden on natural forests. SRCs are not suitable for the welfare and social functions of long-rotation forest management, but they are able to produce large amounts of biomass for energy from a much smaller area at a cheaper cost and can be managed in an environmentally friendly way as well [3].

2.1 Forest yields and short-rotation coppice yields

In the European Union (EU), the mean annual gross increment achieved by forest tree species is 4.7 m^3/ha/year [3]. SRCs have both significantly higher annual revenues and expenditures than long-rotation forests as well as higher carbon sequestration (in the produced biomass) and emission values per year. SRCs are more sensitive to production technology than long-rotation forests. In addition, due to more intensive growth at young age and more intensive production technology, their yearly output is approximately three times more than that of long-rotation forests [3].

After the first and second harvests (**Table 1**), no difference is expected regarding the yield, but after the third rotation, it is necessary to calculate the loss of wood yield, due to the weaker growing ability of the SRC, which can be characterized by an estimated practical factor of 0.85–0.90. In the case of the fourth and fifth harvests, the value of the practical factor is 0.80–0.85 [5].

The duration of the production cycle and the number of cutting cycles are influenced not only by the expected yield data but also by the price of biomass, the actual harvesting cost, and the technical feasibility.

Table 1 shows that if we made our decisions based on the increase in yield, then harvesting after 4 years would be ideal, as opposed to wastewater and sewage sludge disposal, which would be done theoretically every year. All things considered, it seems that there is no solution that is suitable for both the SRC and the wastewater treatment plant. Due to the aspects of the wastewater treatment plant, it is advisable to perform the harvesting earlier, which, in our opinion, may justify harvesting after 2 years, especially in the case of highly productive clones.

Some forest species can be successfully grown in SRC in areas with groundwater inundation, floodplain areas (willow, *Salix* sp.), and even on sandy soils (black locust, *Robinia pseudoacacia*). Under better natural conditions, (hybrid) poplar

Age (years)	Wood mass (t ha^{-1})	Average wood yield (t ha^{-1} yr.$^{-1}$)	Yearly increment (t ha^{-1})
1	12.8	12.8	12.8
2	28.7	14.4	15.9
3	46.9	15.6	18.2
4	69.3	17.3	22.4
5	85.7	17.1	16.4
6	92.0	15.3	6.3
Source: [4].			

Table 1.
Yield data of the "Koltay" poplar clone.

Tree species	Willow	Poplar	Black locust
Yield (t ha–1 year–1)	8.4–25.0	7.8–24.0	5.0–15.0
Source: [5–19].			

Table 2.
Yield intervals of short rotation energy plantations (different species).

(*Populus* sp.) species are most recommended. By planting SRCs in areas prone to erosion or deflation, an excellent soil protection effect can be achieved due to the almost year-round soil cover, and thus their establishment can be a profitable forest alternative for farmers in addition to preserving the rural population. Based on technical literature data on international SRC, the following yield intervals were reported (**Table 2**) [6–20].

As it can be seen in **Table 2**, the yield of SRC shows an enormous variation, depending on the place of production, climate, tree species, and production technology. Furthermore, the yields could be significantly increased, depending on the intensity and management of fertilization.

2.2 The role of woody plants in environmental protection

We consider that biomass has a special place among energy sources in terms of sustainability. It is clearly a renewable resource. However, the balance of GHG emissions moves on a very wide scale compared to the clearly positive balance of other renewable energy sources. This range is mainly influenced by the following factors:

- The amount and nature of the inputs used in the production technology. In this respect, long-rotation forests have lower emissions.

- The biomass yield, which is much higher in SRC than in forests.

- The technology used for energy production: furnaces with medium or large performance (due to the recent legal regulations) have much more favorable environmental characteristics compared to furnaces with smaller performance (e.g., used in family houses, which often have very low-tech combustion units).

- The emission parameters of the substituted energy source; in this respect, the replacements of coal and heating oil are the most favorable.

According to Hungarian regulations, the CO_2 sequestration of 1 ha of average forest area (in the case of natural gas substitution) exceeds the emitted amount of

CO_2 by 3.78 times, and the CO_2 sequestration balance may be 5.3 t/ha/year, based on the authors' previous calculations [3].

CO_2 sequestration in SRC varies widely, depending on tree species, soil quality, and technology intensity [21]. Taking into account these differences and the relevant technical coefficients, the possible amount of CO_2 emissions that can be saved by the different SRCs when replacing natural gas are as follows (t/ha/lifetime): black locust: 23–150, poplar: 35–237, and willow: 35–248 [21, 22].

In accordance with the legal regulations of the given country or production area, we think that the utilization of wastewater and sewage sludge for soil management purposes is possible in the case of both long-rotation forests and SRC. In the case of the latter category, a technology with shorter cutting cycle is preferable than the longer cutting cycle. The harvest is done approximately in every 2–5 years, but some are harvested after 1 year. Accordingly, biomass production and utilization can be realized with this SRC technology in a much shorter and more predictable way compared to long-rotation forests. This fact is compounded by the juvenile growth phase in SRCs, which allows a significant biomass yield to be achieved due to the increased growth rate in the first few years.

Therefore, if not only the waste/by-product utilization function could be achieved, but in addition, the nutrient content of wastewater or sewage sludge could be also utilized for energy production, then the use on SRCs could definitely be recommended.

2.3 Sewage sludge as a nutrient source

Considering our experience, biomass production and the related bioenergy production account for a significant share of the growing energy demand, which is a concomitant phenomenon of economic development and population growth. Due to the—often significant amount of—biomass removed from the soil, in order to preserve the proper condition and productivity of the soils, it is absolutely necessary to perform nutrient replenishment. As a matter of course, the yield of SRC using the wastewater or sewage sludge has a fundamental effect on the amount of energy that can be produced from the biomass removed from SRC. Use of large amounts of wastewater, digested sewage sludge, or sewage sludge compost may result in higher yields, so one can minimize the necessary SRC area to produce enough heat or electricity for the sewage plants' energy self-sufficiency.

Sewage sludge and sewage sludge compost can also be seen as a kind of alternative to chemical fertilizers, especially in areas of nonfood crops [23]. By applying sewage sludge and choosing the suitable SRC, it is also possible to cultivate areas that can be used only to a limited extent or cannot be used at all otherwise [24]. Numerous international examples are known for the use of products containing sewage sludge as raw material in SRC. According to Labrecque-Teodorescu [25], if an adequate amount of sewage sludge is applied on the soil, it has a beneficial effect on the SRC yields. Forest trees are able to absorb significant amounts of nitrogen from the sewage sludge, which helps to achieve higher yields. One of the most critical points in the field use of sewage sludge compost may be the presence of certain heavy metals, which is why the direct application in the case of food and feed production purposes should be avoided. At the same time, in the case of SRC, in addition to the beneficial effects of compost, sewage sludge can also play a direct role in soil remediation: SRC absorbs particularly high concentrations of heavy metals [26]. Moreover, it could be a suitable solution to apply high heavy metal content sewage sludge on the SRC, as it can even significantly reduce the heavy metal content in addition to other nutrients. In this way, it is possible to combine two advantages: on the one hand, the forest trees reduce the harmful heavy metal content, and on the other hand, the resulting biomass becomes usable for energy purposes, improving the economics of the treatment activity [27].

In the case of long-rotation forests, we consider that flooding technology can be used to dispose of a relatively large amount of treated wastewater in one turn (which, in this case, is not hindered even by the unpleasant odor) or to dispose of sewage sludge or compost between rows. However, in both cases, it is a problem that the total yield and, for this reason, the nutrient requirements of long-rotation forests are much lower than those of intensive SRCs, which allows for the treatment of significantly less organic matter in the case of forests. Altogether, compost is less economical than sewage sludge, but its content parameters are more favorable and the health risk of its use is also lower.

In SRC, chemical or organic fertilizer is best applied after harvest. As a result, the application is both technically and economically more advantageous and allows the placement of large amounts of wastewater or sewage sludge compost on a regular basis at short intervals. For all these reasons, we clearly recommend SRC for sewage sludge disposal, although both methods are technically feasible.

By the end of the treatment process, only some of the macronutrients remain in the sewage sludge that can be used for nutrient management. Treated sludge generally contains about 1–6% nitrogen and 0.8–6.1% phosphorus on a dry weight basis [28]. However, an appropriate aerobic or anaerobic treatment is particularly important for sludge utilization.

The nitrogen content of the sewage sludge compost made from digested sludge is approximately 2.1% of the dry matter content [29], while its phosphorus content is half. Consequently, the composition of treated sludge and the sewage sludge compost is significantly lower in comparison with the N and P content of good quality animal manure (8.5 kg/t and 5.5 kg/t, respectively [30]), which, in addition, is not problematic in terms of its heavy metal content either.

The digested sludge yield is approximately 0.3–0.4 kg sludge dry matter/m^3 wastewater [28, 31–33]. In the calculations of the composting technology, a volume ratio of 1:2 was calculated for the sludge and structural material.

The disposal of sewage sludge as compost is also justified by its beneficial effects in terms of forest tree nutrition, soil improvement, and environmental protection. Compared to liquid and dewatered sewage sludge, the use of compost (1) increases the cation exchange capacity of the soil, (2) forms soil granules that improve soil structure and organic matter content, (3) reduces soil erosion, (4) improves soil water management, (5) slows down the release of nutrients, (6) slows nutrient leaching by buffering, and (7) prevents rapid pH change. From the aspect of forest tree nutrition, the use of sewage sludge has the following advantages: (1) it provides more balanced nutrient uptake (less risk of leaching) and (2) it increases the nutrient storage capacity of the soil due to its high adsorption capacity [34, 35].

Wood chips' properties are quite advantageous when applying as a structural material used in composting [31]. In the developed concept, wood chips from SRC serve as a structural material during composting, a significant part of which can be reused after screening.

3. Main characteristics of wastewater management

Approximately, 330 billion m^3 of wastewater is generated on earth in 1 year [36]. However, the proportion of treated water is favorable (70% on average) in developed, economically prosperous countries, while it is only one third or a quarter of all wastewater generated in average in, developing, as well as underdeveloped, poor countries [37]. Accordingly, it can be stated that a significant share of the wastewater produced worldwide is released into the environment without proper treatment and purification.

As for the number of wastewater treatment plants in each continent, Europe is the leader with its 60,000 plants [38], while North America is ranked second (with approximately 16,000 plants). In the ranking of countries, the United States has the largest number (14,600) of wastewater treatment plants.

3.1 Review on sewage plants and wastewater

3.1.1 Energy demand and self-sufficiency

WWTPs are among the largest individual consumers of electricity in municipalities: in some cases, they are responsible for up to 20% of the city's total electricity consumption [39]. For this reason, the treatment of municipal wastewater requires a significant amount of energy, mainly due to the aeration of activated sludge microorganisms—and the operation of the necessary pumps. Its proportion may reach up to 60–70% of the total amount of electricity used [40].

There may be very large differences between different wastewater treatment plants with regard to the electricity used for treatment activities, as this cost group affects operating costs the most. Based on a survey of 369 sewage plants with different technologies examined in the framework of the ENERWATER project [41], it can be concluded that treatment is less efficient in relatively smaller plants (up to 5.50 kWh/m^3) and very efficient in larger plants (up to 0.13 kWh/m^3).

Wett et al. [42] say that wastewater contains more energy than what is sufficient for the treatment plant to use electricity, and with the right technology, the purification activity of the plant can even be self-sustaining.

The energy self-sufficiency rate of plants performing state-of-the-art, efficient treatment, digestion sludge treatment, biogas production, and utilization is 60–100% of their electricity need, depending on their size, and more than 100% of the necessary thermal energy [31]. Consequently, if we use wood chips to improve the self-sufficiency in electricity, we need to find the heat utilization capacity for the extra heat, especially in the summer period. Examples include the following:

- fulfilling the on-site cooling demand,
- using the heat not for only heating of buildings on the site, but for other technological purposes, and
- utilization in a district heating system.

As a matter of course, we think that the level of energy demand of a plant can also be influenced by outdated technology or other modifying factors and conditions (e.g., geographical and site-specific conditions, forest area, or industrial plants nearby) related to the given treatment plant.

3.1.2 Energy and nutrient content of wastewater

From a different viewpoint, nowadays, the approach of wastewater treatment plants is becoming increasingly important, according to which WWTPs can be considered not only as a place of purification activity but also as a source of energy and raw materials. Regarding energy-related characteristics of wastewater, according to McCarty et al. [43] and Gude [44], three forms of energy may be associated to wastewater. For wastewater with an average composition, in the United States, the specific theoretical energy associated to wastewater can be estimated as follows [43]:

1. Energy of organic pollutants: ~1.79–1.93 kWh/m^3
2. Energy to produce fertilizing elements (N and P): ~0.70–0.79 kWh/m^3
3. Available thermal energy: ~7.00 kWh/m^3

The above values were calculated by McCarty et al. [43] based on the chemical oxygen demand (COD) value for the organic constituents present in the wastewater (500 mg/l), assuming a COD theoretical energy production potential of 3.86 kWh/kg.

Similar to the specific energy content of different types of wastewater, their macronutrient contents could also show differences. Municipal wastewater contains mainly water (99.9%) and relatively low concentrations of suspended and dissolved organic and inorganic solids. Organic substances in wastewater include carbohydrates, lignin, fats, soap, synthetic detergents, proteins, and their degradation products as well as various natural and synthetic organic chemicals from the manufacturing industry. **Table 3** shows the levels of the main components of municipal wastewater with high, medium, and low strength, with minor contributions of industrial wastewater. In arid and semiarid countries, water use is often quite low and wastewater has significant nitrogen and phosphorus content. The concentration of raw wastewater also depends on the economic situation of the country and the region as well as its special production activities and consumer habits. Daily wastewater production in developed countries ranges between about 150–300 liters per capita [45].

3.2 Aspects of circular economy

In connection with the wastewater treatment activity and in relation to the concept of circular economy, it is a requirement of recycling to strive for the

Parameter	Concentration, mg/l		
	High	Medium	Low
COD total	1200	750	500
COD soluble	480	300	200
COD suspended	720	450	300
BOD	560	350	230
N total	100	60	30
Ammonia-N	75	45	20
P total	25	15	6
Ortho-P	15	10	4

COD: chemical oxygen demand. The COD analysis measures through chemical oxidation by dichromate the majority of the organic matter present in the sample.
BOD: biological oxygen demand. The BOD analysis measures the oxygen used for oxidation of part of the organic matter.
Source: [46].

Table 3.
Typical composition of raw municipal wastewater with minor contributions of industrial wastewater.

rational use of usable micro- and macroelements in wastewater and composting in order to reduce the volume of wastewater (**Figure 1**).

The utilization of sludge should be considered an integral part of wastewater treatment in order to both reduce the amount of unused wastes and generate valuable products or by-products. Sludge can be used depending on the specific characteristics, circumstances, and regulations of the given country or area. A wide range of solutions and technologies are known, such as landfilling, composting, biogas production, direct utilization on forests, and use in thermal processes [47] (e.g., incineration, pyrolysis, and gasification). Other possible alternatives can be, for example, the utilization in the production of cement [48] or hydrogen [49–51]. In the case of sewage sludge, drying with the help of waste heat and subsequent pelleting is also an option. According to our own previous calculations, primarily, the selling of pellets for heating justify pelleting; the farmer's own use and use for nutrient-related purposes can only be justified in exceptional cases (e.g., if energy and fertilizer prices are very high, or if we cannot utilize the produced heat energy [52]).

In the case of the system established by the sewage plants and the additional technologies organized around them, in order to perform sustainable water management and to preserve and maintain the condition of the natural environment, they must comply with serious international and national regulations, provisions, and directives. The examples presented in Section 5 also illustrate that there are very large differences in the position of each country on the agricultural use of nutrients originating from wastewater.

The topic presented here is primarily influenced by two legal provisions:

1. Regulations on the current emission limit values for plants of different sizes.

2. Legislation governing the disposal of wastewater and sewage sludge compost.

The regulatory environment may differ significantly in each country, but it is important to mention the example of the European Union: the Water Framework

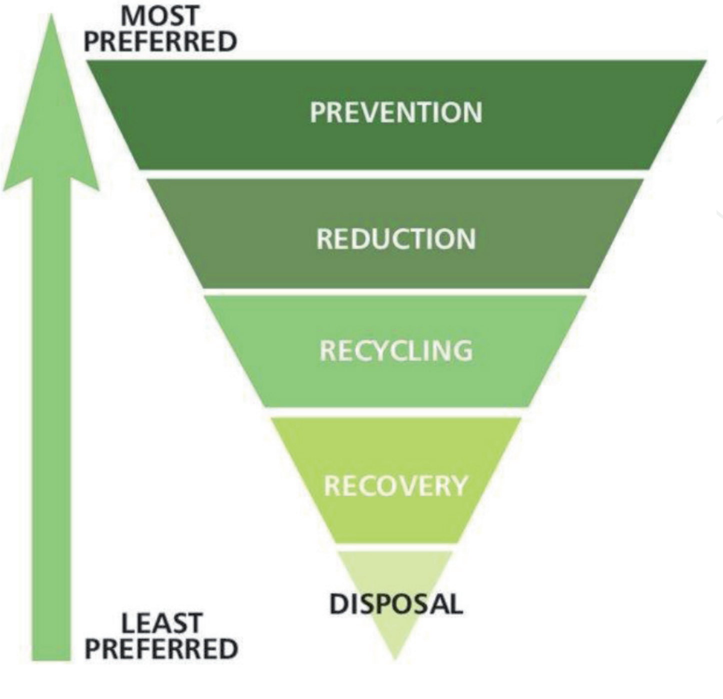

Figure 1.
The waste management hierarchy. Source: [53].

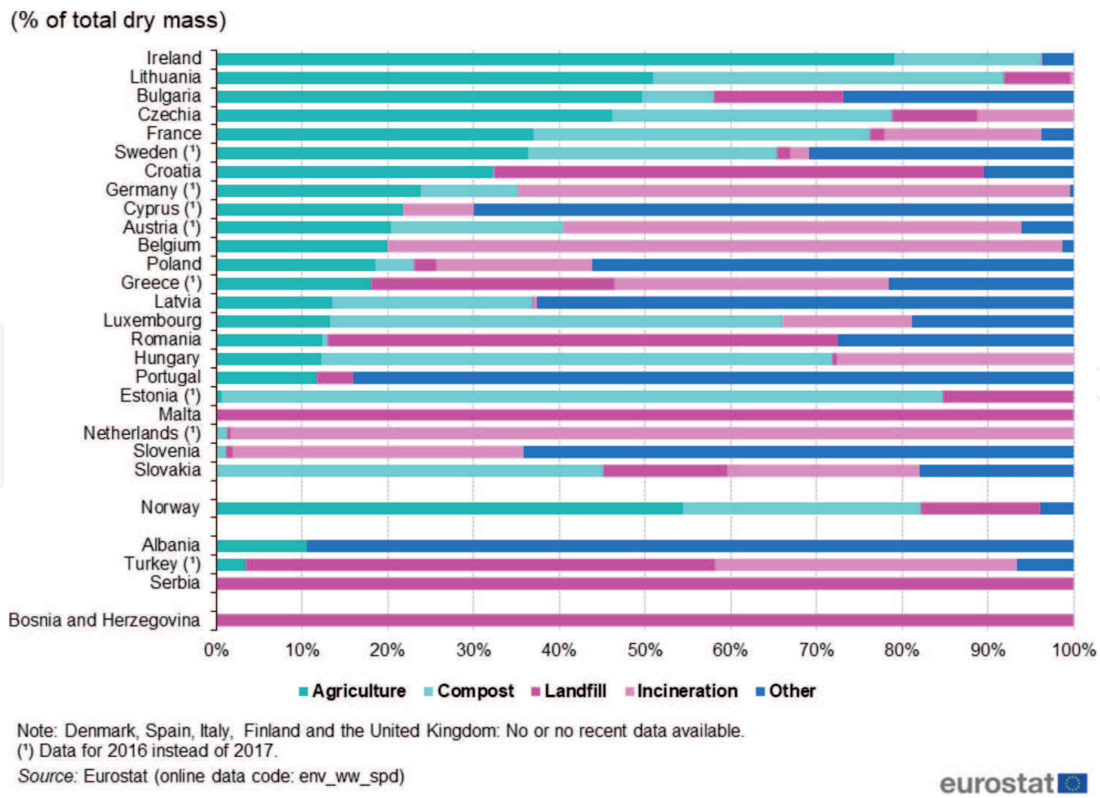

Figure 2.
Sewage sludge disposal from urban wastewater treatment, by treatment method. Source: [54].

Directive (Directive 2000/60/EC) has a uniform water and aquatic environment policy, which was enforced on December 22, 2000. It is a unique goal in this global respect to bring all surface water and groundwater into good condition throughout the European Union. One of the points of this effort is to improve water quality by reducing pollutant emissions, which also includes emission limits for nitrogen (170 kg N active substance/ha). The importance of this EU-related legislation in our case study is to determine the minimum required size of forest or SRC.

According to the latest EUROSTAT register (as shown in **Figure 2**), there are large differences in the methods of disposal in each EU country, and this usually depends on the prevailing environmental and legal regulations in the given country [54].

The most widely used sludge disposal and sludge utilization/treatment alternatives in the European Union include agricultural utilization (directly or as compost), landfill, soil improvement and soil remediation, and incineration.

4. Case study

Below, we present an estimate of the size of an SRC required to utilize the sewage sludge produced by a 250,000 population equivalent (PE)-sized wastewater treatment plant applying the most commonly used technology (activated sludge technology).

Taking into account the average specific amount of digested sludge (0.35 kg sludge dry matter/m^3) [28, 31–33], the resulting total amount of digested sludge is slightly more than 13 t sludge dry matter per day (~4790 t sludge dry matter/year). At the end of a 25–30-day composting process, 3346 t of screened compost dry matter per year can be produced. Calculating with a total nitrogen (TN) content of 2.1% and a 2:1 volume ratio of structural material/sewage sludge, the nitrogen-active ingredient content of the compost is approximately 70 t. According to the relevant EU environmental regulations, the maximum amount that can be disposed of as sewage sludge compost per year is 170 kg/ha of N-active substance. As it is worthwhile or necessary to use sludge in SRC after harvesting, this amount can be applied to 413 ha, calculated with the maximum amount of active nitrogen ingredient that can be applied. This also means that considering SRC with rotation length of 2 years, approximately 826 ha of SRC (twice more) need to be established, as close as possible to the wastewater treatment plant in order to minimize transport costs and alleviate logistical difficulties. One of the reasons for choosing a rotation length of 2 years is that it is a common harvest frequency nowadays in the case of plantations with similar characteristics and purposes, and the amount of both sewage sludge disposal and biomass harvesting is more balanced compared to using a longer rotation length.

According to Gabnai [31], the inclusion of sewage sludge compost utilization—which also results in fertilizer replacement—can reduce the specific cost of wood chips by approximately 10–40%. It is worth mentioning that this value depends on the transport distance, current fertilizer prices, and the market price of wood chips as follows:

- The larger the compost utilization, the price of the substituted fertilizer, and the yield surplus, the lesser the unit cost of wood chip.
- The larger the transport distance and the transport cost, the higher the unit cost of wood chip.
- In case of higher prices of the wood chip or substituted fossil fuel source, the unit cost remains the same, but profit/extra revenue will come in.

In order to ensure the energy self-sufficiency of the wastewater treatment plant, as the amount of electricity from biogas can cover about 70–80% of the plant's energy demand [31], this may be a good opportunity to utilize wood chips produced on SRC for electricity and heat production purposes. In order to achieve full energy self-sufficiency, our calculations were performed on the basis of Patel et al. [55] and Uchman [56] in relation to a gasification plant connected to a cogeneration power plant, taking into account self-produced wood chips at market price.

To determine the required performance of the wood gasifier and the connected combined heat and power technology (CHP) equipment, calculations were performed for the following two approaches:

- Construction and operation of a system with the capacity required to achieve full electricity self-sufficiency.
- Construction and operation of a system with the capacity required to use the total amount of wood chips produced in the areas treated with compost.

Considered specifics and factors in our calculations:

- System useful operation lifetime: 15 years
- Total gas engine efficiency: 94%
    - Gas engine electrical efficiency: 37%

- ○ Gas engine heat generation efficiency: 57%

- Overall system efficiency: 75%

- Electricity self-consumption: 10%

4.1 Construction and operation of a system with the capacity required to achieve full electrical self-sufficiency

The 2.053 million kWh of electricity needed for self-sufficiency, assuming 8000 operating h per year, can be achieved with a system with a capacity of approximately 260 kW_{el}. In the wood gasification unit, taking into account the parameters and efficiency indicated in the study of Uchman [56], this would require 1500 tons of wood chips with 0% water content (atrotons) per year. This quantity, calculated on the basis of the average yield over the entire lifetime of SRC (as detailed in Section 2.1), can be produced on around 120–150 ha of SRC.

When performing system analyses, in addition to the operating parameters, it is important to take into account that, in the initial period, wood chips should be acquired from an external source, as long as the heating energy demand can be covered with self-produced biomass.

4.2 Construction and operation of a power system in order to use all the wood chips produced in compost-treated areas

Alternatively, the required capacity was determined based on the amount of wood chips produced in all compost-treated areas. In doing so, we took into account the operating parameters of the wood gasification + CHP system, assuming a maximum yearly operating time of 8000 operating h, as well as the varying amounts of wood chips produced each year. Based on our calculations, a nearly 1000 kW_{el} system is capable of using up the amount of biomass boasted each year. In our view, sizing based on these considerations can adequately ensure continuous operation.

As Fogarassy and Nábrádi [57] pointed out, in addition to the material and energy saving objectives, significant emissions can be avoided through the above written findings, that is, by eliminating the production and transportation costs of natural gas-based nitrogen fertilizers and by the use of replaced fossil fuel sources (heat energy and electric energy or propellant) by means of avoiding CO_2 emissions.

4.3 Estimated CO_2 emission reductions

Linking wastewater treatment activities to SRC biomass production at the system level allows for emission reductions in the following areas:

- Fertilizer savings and associated CO_2 emission reduction on the SRC
    - ○ Specific CO_2 emissions from fertilizer production
        i. Production of N-active substance: 3.47 kg CO_2/kg active substance [58]
        ii. Production of P_2O_5-active substance: 0.54 kg CO_2/kg active substance [58]

- CO_2 emissions of fossil fuels replaced by the use of the biomass produced (either through energy self-sufficiency or the sale of surplus energy)

    - Electric energy production output: 0.706 kg/kWh [59]

    - Heat energy production output: 0.273 kg/kWh [59]

These specific units can be used to estimate the CO_2 emission savings if we use sewage sludge instead of N- or P-fertilizers as well as if we use renewable electricity instead of fossil-based ones. Each of them includes uncertainties. Since there are many differential N- and P-fertilizers, with differential N- and P-content and with differential production technologies, we did not make any calculations for estimating their CO_2 savings. Considering the substituted energy sources, we considered the renewable heat instead of natural gas (which is the typical fossil fuel in wastewater treatment plants) and renewable electricity instead of the typical electricity mix in Hungary. Taking into consideration the abovementioned assumptions, the use of an SRC connected to a wastewater treatment plant with 250,000 population equivalents using cogeneration technology, the following amount of yearly CO_2 savings can be estimated:

1. Construction and operation of a system with the capacity required to achieve full electricity self-sufficiency

    - 1450 t of CO_2 connected to eliciting of electricity

    - 380 t of CO_2, if the surplus heat energy can be utilized

2. Construction and operation of a power system for the use of the total amount of wood chips produced in the areas treated with compost

    - 5650 t of CO_2 connected to the electricity savings

    - 1490 t of CO_2 connected to the heat energy savings

The achievable environmental impacts are also significantly influenced by the country's energy mix and the specific CO_2 emissions of the energy sources used to ensure the operation of the system.

5. International examples

Irrigation with wastewater dates back thousands of years and can be traced back to water scarcity and the need to utilize the valuable nutrients it contains. As technological efficiency improves, so does the rate and quality of treatment, which creates even more favorable conditions for wastewater irrigation, reducing environmental and social risks. Examples are known for the disposal of both wastewater and sewage sludge as well as for the implementation of nutrient replenishment in field crop production, in the different horticultural sectors and forestry as well as in biomass production for energy purposes. According to Zhang and Shen [60], while complying with relevant regulations, the rate of direct recycling of treated wastewater increases by approximately 10–29% every year in the EU, the United States, and China, while in Australia it is 41%. The situation is significantly worse in developing and lagging countries.

Although in many parts of the world, the disposal of wastewater or sewage sludge on arable crops is only minimally or not at all restricted, it may be favorable to apply it in long-rotation forests or SRC in order to avoid social risks.

In the next section, examples of use of wastewater, sewage sludge, and sewage sludge compost in forests in different countries are presented.

5.1 Egypt

Due to the dry climate and minimal water resources, 95% of Egypt consists of deserts and marginal areas unsuitable for crop production. Accordingly, most of the arable land is located in and around the Nile Valley. The River Nile has been the main source of water for agriculture and households since ancient times, but recycled wastewater has also emerged as another significant source. Due to the relatively low nutrient content, high treatment costs, as well as environmental and health problems, wastewater appears unsuitable for irrigating food-producing areas. At the same time, there is great potential for irrigating high-value industrial forests in desert areas. To this end, afforestation projects were started around the turn of the millennium based on raw and primarily treated wastewater. In this way, it is possible to contribute to the rehabilitation of dry, desert areas using wastewater. Successful attempts have been made to implement both short- and long-rotation coppices with trees of different species such as Sesbania (*Sesbania bispinosa*), Casuarina (*Casuarina equisetifolia*), Eucalypt (*Eucalyptus regnans*), Khaya (*Khaya anthotheca*), and Jatropha (*Jatropha curcas*). In addition to the involvement of land in production, this activity can also be of great importance for the implementation of a sustainable supply of feedstock as well as the production of industrial or energy wood and other high value-added downstream products [61].

5.2 South Africa

As a result of gradual economic development and population growth, the amount of wastewater generated is also increasing significantly, especially in developing countries and regions. In Durban, fecal sludge from pit latrines was buried using deep row entrenchment. Then forest trees were planted over the area, leaving about a meter of soil between the sludge and the surface. In the first small plot experiments, trees were planted on the buried sludge. As a result of the experiment, the sludge also had a beneficial effect on the growth and health of the trees. In addition, monitoring in the area showed that 3–4 years later the groundwater was not polluted and pathogenic organisms were not present either. As a result of this research, it can be concluded that, although there is a risk of soil contamination, the above example can be mentioned as a promising, simple, cost-effective, and safe sludge management option with controlled application, which also results in significant fertilizer replacement [62].

5.3 Estonia and Latvia

In both countries, sewage sludge from wastewater treatment plants and sewage sludge compost were delivered to SRC established with willow species. In addition to increasing biomass yields, the goal was to properly dispose of sewage sludge and replenish soil nutrients. In addition to complying with environmental and soil protection regulations, a significant increase in biomass yield was observed in each experiment, starting from the second harvest [63, 64].

5.4 Sweden

An example of the use of treated wastewater and sewage sludge in an SRC is Enköping (Sweden), where a phytoremediation-bioenergy project involves the application of 200,000 m^3 treated wastewater and sludge on a 75-ha SRC willow (*Salix* sp.) plantation. As a result, by utilizing the N and P content of wastewater, fertilizer costs can be significantly reduced and an increase in biomass yield of more than 50% can be observed.

An excellent example of the link between circular economy and wastewater management is the Swedish Hammarby Sjöstad project (Stockholm), which implemented an integrated closed wastewater energy system based on municipal wastewater. Until 1998, the site was an industrial area where significant amounts of oil, heavy metals, and other contaminants had accumulated earlier. Accordingly, the development of the area had to begin with purification. The aim of the designers was to reduce the environmental impact by half by environmentally conscious and modern planning of land use, public transport, construction, energy, as well as water and waste management, and by maximizing circular processes, thus moving toward environmental and economic sustainability [65].

5.5 Poland

Fijałkowska et al. [66] carried out a field experiment with three willow (*Salix viminalis*) clones, applying compost from the municipal sewage sludge, where different treatments with fertilizer were used in order to assess the remaining amounts of alkaline elements and heavy metals in the soil up to 90 cm of depth. The compost from the municipal sewage sludge proved to be a useful amendment in the production of willow biomass due to a considerable content of biogenous substances and alkaline metals, together with a low content of heavy metals, as well as little odorous noxiousness for the environment.

5.6 China

China produces an enormous amount (more than 30 million t) of municipal sewage sludge annually, with a yearly increase of 10% [67], thus sewage sludge disposal has become a significant challenge in China as well. Chu et al. [68] applied sewage sludge compost as a fertilizer and conducted an experiment to investigate the effects of compost on *Mangifera persiciforma* growth and quantified its uptake of heavy metals. As a conclusion, consistent with other studies (with species such as *Larix decidua* [69] and *Pinus radiata* [70]) focusing on sewage sludge compost's effect on different species, Chu et al.'s experiment clearly indicated that the application of sludge compost is an effective way for improvement of *M. persiciforma* growth. As a result, plant height, ground diameter, and biomass yield have significantly increased by the application of sludge compost. Their findings suggest that sewage sludge compost at reasonably low application rates can promote the growth of the landscape tree with minimal risk of contaminating landscaping soil with heavy metals [68]. It can be added that health risks can be minimized if the material generated at the sewage plant is disposed on the areas planted with only forestry tree species.

6. Conclusion

Wastewater and sewage sludge, as energy- and nutrient-rich materials, can contribute to increasing the yield of woody biomass (forests, SRCs). This woody biomass is suitable for the environmentally sound disposal of sewage sludge or treated wastewater, and it can contribute to increasing the energy self-subsistence of the wastewater plant or even extra energy generation.

The utilization of sewage sludge for nutrient management is a serious problem to be solved, especially in the case of industrial wastewater. In contrast to arable land used for food crops, high levels of inorganic matter and, in some cases, relatively high levels of heavy metals do not pose a food safety threat in the case of forest biomass.

Using large amounts of wastewater, sewage sludge, or sludge compost—complying with environmental regulations of the specific area or region—may result in higher yields, so one can minimize the necessary SRC area to produce enough heat or electricity for sewage plants' energy self-sufficiency. In this way, it is possible to combine two advantages: on the one hand, the tree reduces the harmful heavy metal content of soil, and on the other hand, the produced biomass becomes usable for energy purposes, improving the economic characteristics of the wastewater treatment activity. Due to the aspects of the operation and sludge production of the wastewater treatment plant, it is advisable to perform the harvesting earlier, which, in our opinion, may justify harvesting after 2 years, especially in the case of intensive management.

Based on our case study, approximately 826 ha of SRC (with a 2-year rotation) are required for the disposal of sewage sludge generated by a 250,000 population equivalent wastewater treatment plant. Considering the wastewater treatment plant's electricity self-sufficiency, 120–150 ha of short-rotation coppice would be well enough. This complex system can avoid the emissions of 5650 t of CO_2 via electricity generation and another 1490 t of CO_2 through utilization of waste heat.

It should be highlighted that the achievable environmental impacts are also significantly influenced by the country's energy mix and by the specific CO_2 emissions of the energy sources used to ensure the operation of the system.

It can be concluded that the bottleneck of this two-sided sizing technique is the waste disposal. Thus, there is a need for much higher SRC area compared to the area demand of electricity self-sufficiency in the WWTP. Joint design of WWTP and SRC may be a potential reserve in economic and environmental operation.

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