THE POSSIBLE ROLE OF URBAN WASTEWATER TREATMENT PLANTS IN NUTRIENT- AND ENERGY MANAGEMENT

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Abstract

In our article, we deal with the potential role of wastewater plants in energy generation and nutrient management. We primarily deal with larger size plants, since in these plants there is a wider spectrum of energy and nutrient management options. This is due to, inter alia, economies of scale, higher amounts of homogeneous raw material and, consequently, easier utilization and qualification of different products.

In our estimates we have found that a purification plant using anaerobic technology for a population of 100,000 households can produce 2900 m^3 of biogas per day and from this about 1900 m^3 per day of biomethane. As regards the nutrient management of the site, the amount of the macro-element content of the incoming wastewater, which is approximately 13,000 m^3, is 281.000 HUF (~ EUR 900) of TKN (Total Nitrogen, 1.3 t/day) and 68.000 HUF (~ EUR 220) of TP (total phosphorus 0.2 t/day). In the outgoing purified water there is a TKN of HUF

42.000 (~ EUR 133), and a TP of HUF 4.400 (~ EUR 14). The methods and the values used in the calculations can serve as basic data for further comparative tests and potentials for different size plants.

Keywords: sludge, sewage plants, urban waste, biogas, biomethane

Összefoglalás

Cikkünkben a nagyvárosi szennyvíztelepek energiatermelésben és tápanyag-gazdálkodásban betöltött lehetséges szerepével foglalkozunk. A tisztító telepi kategóriák megemlítése mellett elsődlegesen a nagyobb méretű telepekkel foglalkozunk, ugyanis ezeken a telepeken szélesebb az energetikai és tápanyag-gazdálkodási lehetőségek spektruma. Ennek oka többek között a méretgazdaságosság, a nagyobb mennyiségű homogén alapanyag, és ebből adódóan a különböző termékek könnyebb hasznosítási lehetőségei, minősítése (pl. a homogén minőségű és mennyiségű rothasztott iszap termelése és hasznosítása).

Cikkünkben bemutatjuk, hogy nagy jelentősége van a rendszerszintű tervezésnek, és a körfolyamatok beépítésének, amely által az egyébként klasszikus értelemben vett hulladékból (szennyvízből) komoly értéket képviselő termék állítható elő. Éppen ezért a keletkező szennyvíziszap hasznosítása terén az esetleges égetés vagy hulladéklerakókba történő kihelyezés alternatívájaként minél teljesebb módon szükséges megvizsgálni a mezőgazdaságban történő hasznosítás lehetőségeit. Becsléseink során azt kaptuk, hogy egy 100.000 lakosegyenérték méretű, anaerob technológiát is alkalmazó tisztító telep gázvonalán napi szinten 2900 m^3 biogáz és ebből nagyságrendileg 1900 m^3/nap biometán termelhető. A

telep tápanyag-gazdálkodását illetően a telepre érkező – megközelítőleg 13.000 m^3 mennyiségű – szennyvíz makroelem-tartalmának értéke 281 ezer Ft TKN (összes Nitrogén; 1,3 t/nap), illetve 68 ezer Ft TP (összes foszfor; 0,2 t/nap). A kimenő tisztított vízben pedig 42 ezer Ft értékű TKN, illetve 4,4 ezer Ft értékű TP található. Az általunk a számítások során meghatározott értékek alapadatként szolgálhatnak további vizsgálataink, valamint eltérő méretű telepek potenciálbecslése céljából.

Introduction

Around the world, an increasing proportion of the population are moving to cities and producing increasingly large quantities of waste, the major (and difficult to handle) part of which is produced in liquid form. In contrast to smaller settlements, industrial plants operating in cities also emit large quantities of often hazardous organic matter, which should be managed together with household sewage, preferably in an automated and cost-effective way, with anaerobic fermentation and other technological solutions, to produce renewable energy. In addition, there is a great potential for utilizing the macro and

microelement content of the organic material in the wastewater from the plant. In our article, we deal with the potential role of these large city wastewater plants in energy generation and nutrient management. The role and potential of sewage in nutrient management are fundamentally determined by current environmental regulations and economic and financial conditions. At the same time, it can be stated that the raw materials, macro and microelements - generally used in agriculture - are present in large amounts in sewage and therefore, depending on the different utilization methods, the measurement of their quantity and value is in any case justified.

Literature review

Today, due to increases in population and living standards, the amount of water used is constantly growing. Agriculture is responsible for 70% of global water use, 11% is for urban, residential use, and 19% for industrial water demands (UNESCO, 2017). By contrast, water scarcity is constantly increasing, driven by climate change and changing consumer habits ("water-intensive" foods, for example, meat consumption in the developing world, as well). In the 21st century, water scarcity is one of the biggest global problems: according to the FAO, by 2025 1.8 billion people will live in physical water scarcity (Internet1).

Another trend is that an increasing proportion of the population are moving to large cities; the share of urban population is over 50% globally, while in Hungary it is almost 70% (Kovács, 2017). The population flow to cities is very rapid: in global, their population is growing by about 200 thousand a day, and the area they occupy by 110 km2, and the proportion of the population living in cities of more than one million is over 27% (Internet2). The wastewater management problems of villages and cities, and the possibilities for applying technology differ greatly, not only because of the different size and the different regional roles of these settlements, but also because of the different income levels and wastewater quality. Villages are smaller and closer to nature, with more restricted purification efficiencies, while in large cities, due to the more concentrated and larger quantities of industrially polluted wastewater, large-scale automated, predominantly sludge-based sewage treatment plants are characteristic

(Bodáné Kendrovics, 2018). At the same time, there are other demands made on the large plants, and in addition to waste management tasks, in most places there is a need for anaerobic gasification, the production of heat and electricity, and occasionally (e.g. in Zalaegerszeg, Hungary) serving some local transport needs. In this context it can be stated that changing consumer/decision makers' attitudes in transport may help to promote the spreading of sludge based transport fuels, too (Jámbor - Mizik, 2008).

The three-stage water-energy-nutrient model is closely related to sewage treatment, so the efficiency, quality and other characteristics of the cleaning activity carried out have an impact on the environment, on society and on the economy, as well.

The amount, characteristics and value of the wastewater produced

According to FAO data, nearly three hundred billion m^3 of wastewater is generated over the course of a year on Earth. However, as regards cleaning it, it can be said that in the developed countries with a good economy the proportion of water purified is good (on average 70%), while in average and developing countries and poor countries, this proportion is on average only one third, or one quarter (Sato et al., 2013). Accordingly, around 80% of the wastewater produced around the world is estimated to be released into the environment without appropriate treatment, or purification (UNESCO, 2017).

According to McCarty et al. (2011), energy in wastewater is present in three forms. The specific theoretical amount of energy in sewage water considered average in the USA is as follows:

1. The energy of organic pollutants: ~ 1.93 kWh / m^3

2. The energy of plant nutrients 2 (N and P): ~ 0.79 kWh / m^3

3. Heat energy: ~ 7.0 kWh / m^3

The above values were measured by McCarty et al. (2011), calculated on the basis of the COD (Chemical Oxygen Demand) value for the organic components present in the wastewater (500 mg/l), assuming a theoretical power generation potential of 3.86 kWh/kg. In Hungary, this value is somewhat higher, and the wastewater is more concentrated due to the lower water consumption per capita. In addition, it is worth noting that the concentration of crude wastewater depends on several factors (depending on the country or region’s economic situation, specific production activities, or water scarcity).

Types of cleaning plants, factors influencing their size

The size of the cleaning plant is fundamentally influenced by the energy and nutrient management potential. The purification technologies can be divided into two types, following Dittrich (2016): intensive and extensive technologies (Table 1).

Table 1. Categorization of sewage treatment technologies

1. Intensive technologies	2. Extensive technologies
1.1. Sludge processes: - Traditional - SBR - Oxidization ditch - etc. 1.2. Fixed-film procedures: - Drip bodies - Disc, etc.	- Sewage purifying lakes, built wetlands, flowing over the surface - built wetlands, flowing under the surface wetlands: root zone wastewater treatment - Soil filtration, soil spraying - Skimming - Pebbles and sand filters, etc.

(Source: authors’ own editing, based on Internet3)

Among these technologies, the combination of intensive sludge effluent treatment and close-to-nature cleaning (plant and animal ecological community) is the so-called "living machines" cleaning technology. The purifier - which includes the classical anaerobic-anoxic-aerobic chain and plants on a lattice, as well as microorganisms and even higher-level animal organisms - is housed in a greenhouse-like building (Grant et al., 2012 IN: Veres, 2015). In this way it is partly possible to compensate for fluctuations in winter temperature and efficiency fluctuations, and the irritating smell can be reduced.

Based on TESZIR's records (Települési Szennyvíz Információs Rendszer / Urban Wastewater Information System), only 25 of the 574 plants in Hungary have a capacity of above 100,000 PE (population equivalent), while these plants account for more than half of the total cleaning capacity (Internet 3). Generally speaking, most of the wastewater is cleaned by larger size cleaners typically based on activated sludge technology. Sewage plant biogas production is carried out in 30 plants and - with one exception - is carried out in plants of at least 50,000 PE capacity. This is confirmed by Kárpáti (2016), who designates a 20-40 thousand PE capacity as the lower limit of the economic feasibility of biogas production.

Significant changes have been made in sewage sludge placement over the past decades. Prior to the millennium, sewage sludge was rendered harmless in seas or placed on agricultural land. Since 1998 the European regulations – the Urban Waste Water Treatment Directive (UWWTD) - have banned the disposal of sewage sludge in seas. As a result, a significant portion of sewage sludge (35-45%) has found its way to landfills (Rózsáné Szűcs, 2013). Changes in utilization ratios have moved in a favourable direction towards recycling in the last decade, and sewage sludge is considered a potential source of raw material (Gabnai – Gál, 2016).

Linkage of the circular economy to sewage treatment

In areas such as sewage treatment, where significant quantities of waste and by-products are processed, disposed of and possibly re-used or prepared, it is of the utmost importance to keep in mind sustainability and environmental awareness criteria. A wastewater treatment plant has the ability to "let through" the incoming material, which represents a

significant nutrient and energy content, without making use of any energy or material content, simply applying the mandatory cleaning function. In contrast, it is also possible to exploit the potential of either energy self-sufficiency or even surplus energy production and substantial nutrient re-utilization. The latter also includes the approach represented by the circular economy, where emphasis is placed on minimizing losses, reuse and recycling (Geissdoerfer et al., 2017 IN: Kiss T., 2018). We need to grow food on even less land and with less water, using less energy, in the future than today for feeding more and more people (Popp et al., 2014), so with the energy use of wastes (e.g. sewage) instead of plants we can save significant amount of land (Popp et al., 2018).

Methodology

In our article, in addition to mentioning the cleaning plant categories, we primarily deal with larger size plants, since in these plants there is a wider spectrum of energy and nutrient management options. This is due to, inter alia, economies of scale, higher amounts of homogeneous raw material and, consequently, easier utilization and qualification of different products (e.g. production and utilization of homogeneous qualities and quantities of sifted sludge).

In our estimate - in the context of the circular economy concept - we determine the quantity and quality of product that can be produced for a unit-sized sewage plant (equivalent to the sewage produced by 100,000 adult inhabitants), as well as the value of the macro elements in wastewater. Our calculations include the following considerations:

• Biogas production and biomethane production potential

• The macro element content of the water arriving to the plant and the purified wastewater and its value

• The amount, nutrient content and utilization potential of matured sludge

Estimated basic data of a 100,000-inhabitant equivalent purification plant (based on data of Kárpáti, 2014):

• Amount of incoming, purified sewage: 13,000 m^3/day

• Biological oxygen demand: 6,000 kg/day

• Daily excess sludge yields: 0.7 kg MLSS/kg BOI

• MLVSS/MLSS ratio: 0.85

• COD (Chemical oxygen demand)/MLVSS ratio: 1.5 kg COD/kg MLVSS

• Specific methane content: 0.35 m^3 methane/kg of COD

Basic data used to calculate the value of (or monetary value of the) nutrient content of sewage:

• Nitrogen active ingredient: ~ 216 thousand HUF/tonne (~ EUR 690)

• Phosphorous active substance: ~ 339 thousand HUF/tonne (~ EUR 1,080)

Calculation: average data are taken from KSH (Central Statistical Office) (Internet 4).

The macro element content of the incoming and outgoing sewage, and wastewater sludge compost, taking into account Kárpáti's (2014) data:

- Incoming sewage TKN: 91-112 g TKN/m^3 (mg/l)

(TKN - Total Kjeldahl Nitrogen - Amount of Ammonium N and Organic N)

- Incoming sewage TP: 14-16 g TP/m^3 (mg/l) (total phosphorus)
- Outgoing sewage TKN: 15 g TKN/m^3 (mg/l)
- Outgoing sewage TP: 1 g TP/m^3 (mg/l)
- Compost TKN (in dry matter): 2.1%
- Compost TP (in dry matter): 1%

Results

Yield estimates for energy and nutrient management

Biogas Production Potential

On the basis of our calculations we can calculate the amount of biogas produced daily in anaerobic sewage sludge digestion process (based on technological parameters), as 2900 m^3, from which 1900 m^3/day biomethane can be produced. Based on these products, two main ways of utilization can be identified:

(1) Co-generation utilization: both heat and electricity are generated. The primary purpose of co-generation is to pursue energy self-sufficiency.

In the literature, several plants have been identified in which an energy self-sufficiency of more than 100% has been realized and where surplus commercial biogas is even sold (typically German, Austrian, Czech, British and American plants) (Shen et al., 2015). The cornerstone of economical operation is in this case the utilization of the waste heat generated in the process, which accounts for about 55-60% of the generated energy. The efficient and complete use of waste heat is made difficult by the fact that not only is the heat energy self-consumption reduced in the summer, but also the amount of biogas produced is higher than in the winter period, so it is rather problematic to plan continuous and complete heat utilization. Naturally, the fact that during the summer season the household heat demand decreases also contributes to this. During this period, it is possible to meet the technological heat demand of production plants.

(2) Biomethane purification and recovery: purification of biogas using a special method, followed by its use in the natural gas network or propellant.

In the developed EU Member States, biomethane has become relatively widespread in the natural gas network and as a fuel for transport. The latter is also considered to be significant in some developing countries (Argentina, Iran, India). When biomethane is used as a propellant, more economical results are achieved, while the production of marketable finished products means that in the case of co-generation it is partly impossible, and with biomethane production completely impossible, for a sewage plant to achieve energy self-sufficiency. Only two biogas production plants (Zalaegerszeg and Kaposvár) produce biomethane in Hungary, because most of the domestic wastewater plants tend to use biogas to meet their own technological heat and electricity needs.

The quantity and nutrient content of the incoming and outgoing water flow

In Table 2 it can be observed that the macro-element content of the 13,000 m^3 of waste water per day at the sewage plant is significant, for both incoming (HUF 281 thousand / EUR 900; and HUF 68 thousand / EUR 220) and outgoing (HUF 42 thousand / EUR 133; and HUF 4.4 thousand / EUR 14) wastewater.

Table 2. Quantity and nutrient content of the incoming and outgoing water flow

		Macro-element	
Description	Measure	TKN[1]	TP[2]
Amount in incoming sewage water	mg/l	100	15
Daily amount	t	1.3	0.2
Unit price	HUF/t	216	339
Value	thousand HUF/day	281	68
Amount left in output sewage water	mg/l	15	1
Daily amount	t	0.195	0.013
Unit price	HUF/t	216	339
Value	thousand HUF/day	42	4,4

(Source: authors' own calculation)

[1]*Total Kjeldahl Nitrogen - ammonium N and sum of organic N*

[2]*all Phosphorus content*

Volume, nutrient content and utilization potential of sludge

Taking into account that the resulting biological sludge yield is approximately half of the amount of matured sludge, according to our calculations, and assuming a 25% dry matter content, approximately 8.4 m^3 per day (~ 3060 t/yr) of rotted sludge is produced. For the composting of this quantity, based on Kárpáti's (2014) 2:1 structural material/sewage sludge ratio, it would be necessary to use 1500 t/year of wood cuttings (structural material). A part of the structural material is re-deposited for later use, and so according to our calculations, a total volume of 1070 t/year of sieved compost is produced. The dry matter content of this composting material (40%) is 430 tonnes, of which the total

nitrogen content is approx. 9 tons. With 170 kilograms of active substance/ha/year, this is a total area of 53 hectares, which, however, can change according to the site conditions and other characteristics. The amount of phosphorus - assuming a 1% P content - is 4.3 tons of active substance per year.

Their theoretical monetary value:

• Nitrogen: HUF 1,947 million

• Phosphorus: HUF 1,456 million

Concerning the above calculations, it should be added that, in practice, the utilization of macro elements can be influenced by a number of production site conditions. According to Dulovics (2012), depending on soil conditions and farming practices, the N-supply of sludge or compost can be used over 3-10 years. According to the lessons learned from field and propagation experiments, N is only partially incorporated – and then only a proportion of it - into the persistent humus material of the soil.

Where the use of sewage sludge compost would cause concerns and risks (in areas producing crops for food), a good solution can be to apply it to energy plant production, where, as well as other nutrients, it is capable of significantly reducing the heavy metal content. In this regard, several attempts have been made to assess the extent to which a herbaceous energy plant can reduce the heavy metal content of soil or sewage sludge and, at the same time, the level of (excess) biomass it can yield. In this way it is possible to combine two advantages: on the one hand the plant reduces the harmful heavy metal content and on the other hand the resulting biomass can be used for energy purposes, improving the efficiency of the cleaning operation. Sewage sludge can thus beunderstood as an alternative to fertilizers (Nabel et al., 2016). In the paper by Pszczółkowska et al (2012), the authors summarize the lessons learned from articles on using sewage or sewage sludge as a nutrient supply for various energy crops. According to the article, in addition to application of sewage - which in many cases improves the pH of the nutrient supply as well as replacing nutrients - the yield of the sida energy crop is on average 9-11 tonnes of dry biomass. The nutrients, micro and macro elements from the sludge are also efficiently utilized by willow species and 20 t/kg were found to have beneficial results for miscanthus (Chinese-reed), while in other research, amounts above 60 metric tons were used effectively as an alternative to conventional fertilizers. The fertilizer application (in an NPK mix of 90:70:90 kg/ha) increases the yield of miscanthus by 96%, while it is increased by 81% by the application of 63 t/ha of sewage sludge (Kurucz et al., 2014). With the use of digested affluent, Paulownia tomentosa (Vityi – Marosvölgyi, 2014) plantations also may support site remediation and biomass production.

In addition to materials and energy saving targets, significant emissions can be avoided, primarily through the replacement of the production and transportation costs of natural gas-based Nitrogen fertilizers, and the avoidance of the CO_2 emissions which accompany the use of fossil fuels (heat and electric energy, or fuels). Present agricultural GHG reduction projects in Hungary cannot contribute to achieving long term GHG reduction goals to the same degree as can be experienced in other sectors due to food market insecurities, production limitations and the decreasing exchange quotation of GHG emissions. Consequently, climate-friendly agricultural investments have more advantageous returns than in other sectors (Fogarassy – Nábrádi, 2015).

Good practices in sewage management

Below, we introduce a Swedish example that illustrates the possibilities well. The Swedish city of Hammarby Sjöstad (Stockholm, Sweden), often referred to as a model example of a sustainable city, is the result of a complex, well-designed, system-level plan that every year attracts the attention of more than ten thousand experts and decision-makers in sustainability and other areas. A precondition of the efficient operation of the system which – in addition to efficient implementation - embraces the concept of a circular economy, is the mapping of the exact features, characteristics and symbiotic connections of the elements of the system (waste management, energy, water management, agriculture and other areas). It is interesting that until 1998 the area was an industrial area where significant amounts of oil, heavy metals and other contaminants had accumulated. Accordingly, the development of the district had to be started by cleaning the area. The aim of the planners was to reduce the environmental load by half through an environmentally conscious and modern planning of land use, public transport, construction, energy and water and waste management, and maximizing cyclical processes, thus moving towards environmental and economic sustainability (Figure 1):

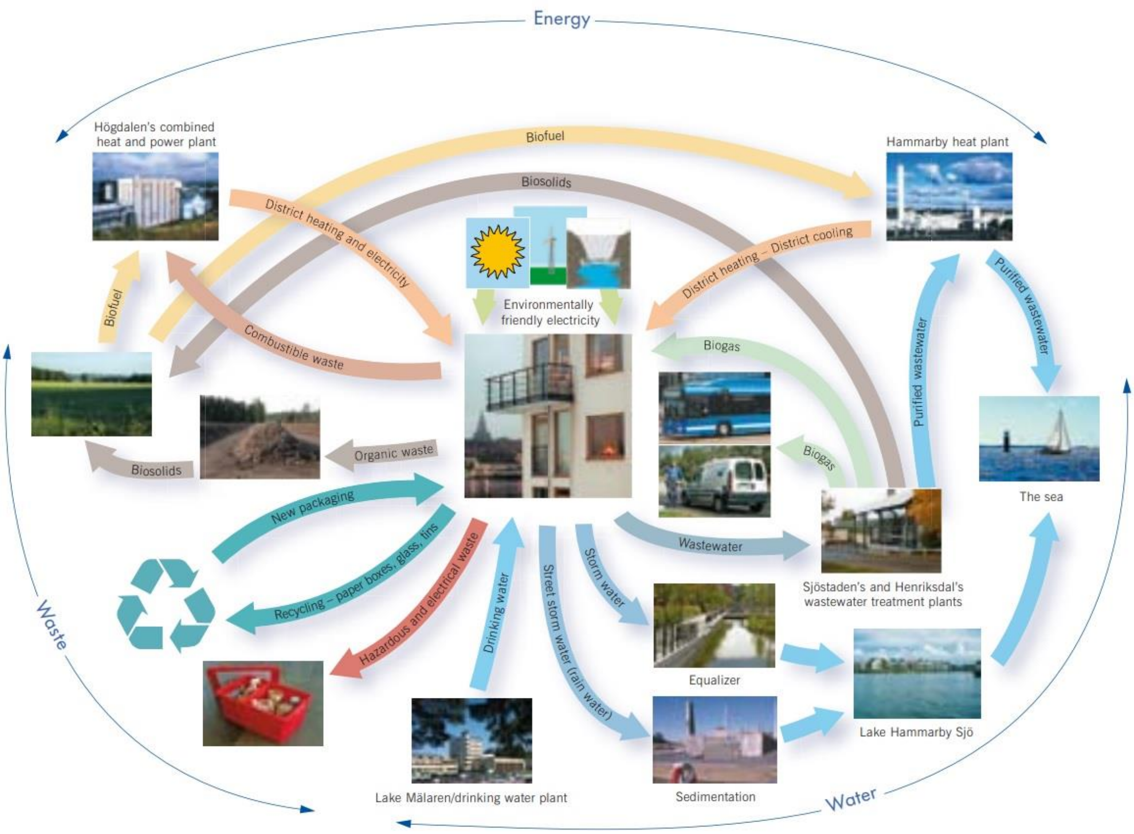

Figure 1. The complex system of Hammarby Sjöstad
(Source: Internet6)

An interesting example of soil management based on significant amounts of sewage sludge is the Carson Wastewater Treatment Plant (Los Angeles, California). The plant has been producing sewage sludge for sixty years now and has been operating an open prismatic composting system for thirty-five years. However, due to the increasingly stringent requirements, a modern composting plant has become necessary, for which 5900 hectares of property was selected in the central valley of California's agricultural zone, to create a composting capacity of one million tonnes per year. The plant produces a Class I sewage sludge that is used in surrounding agricultural areas to restore nutrient supply to the soil.

Summary

Nowadays, the use of energy and materials related to human activity, as well as the related environmental load, is taking on ever greater dimensions. All this places great emphasis on the need to use technologies and solutions that can contribute to making processes as sustainable as possible. In the case of cleaning plants, due to the requirement for good quality waste disposal and purification, the need for material and energy-saving operation is increasingly emphasized. Moreover, the above expectations can be seen in a significant amount of energy production processes, or even in terms of nutrient supply and reclamation. Naturally, in the field of water and waste management, the importance of extracting energy and nutrients from sewage has been evident from time to time, and serious endeavours and initiatives aim at achieving the most sustainable and environmentally conscious operation.

As we have seen in the article, system-level planning and the integration of cyclical processes is of great importance so that waste (sewage) as understood in a classical sense can produce a product of high value. With the advance of technology and the full exploration of the possibilities, energy can be produced in excess of the energy needed for cleaning, and a significant proportion of the nutrients can be utilized as part of the cycle. Macro nutrients in outgoing sewage and sewage sludge represent a significant value and can today contribute to generating enormous amounts of fertilizer and to reducing costs. Sewage sludge can be placed in a food-producing area in compliance with the relevant standards, but can also be utilized to great effect in energy crops in areas with less-favoured characteristics or excessive heavy metal content. All of these can also be recycled into the process, as wood shreddings can be an important raw material for composting. Therefore,

when considering the utilization of sewage sludge its possible use in agriculture should be investigated in the most comprehensive way as an alternative to possible incineration or landfilling. In our estimates we have found that a purification plant using anaerobic technology for a population of 100,000 households can produce 2900 m^3 of biogas per day and from this about 1900 m^3 per day of biomethane. As regards the nutrient management of the site, the amount of the macro-element content of the incoming wastewater, which is approximately 13,000 m^3, is 281 thousand HUF (~ EUR 900) of TKN (Total Nitrogen, 1.3 t/day) and 68 thousand HUF (~ EUR 220) of TP (total phosphorus 0.2 t/day). In the outgoing purified water there is a TKN of HUF 42 thousand (~ EUR 133), and a TP of HUF 4.4 thousand (~ EUR 14). The methods and the values used in the calculations can serve as basic data for further comparative tests and potentials for different size plants.

Acknowledgments

This research was supported by EFOP-3.6.2-16-2017-00001 project (Research of complex rural economic and sustainable development, elaboration of its service networks in the Carpathian basin).

The research was financed by the Higher Education Institutional Excellence Programme (20428-3/2018/FEKUTSTRAT) of the Ministry of Human Capacities in Hungary, within the framework of the 4.thematic programme of the University of Debrecen.

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