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Analysis of efficacy of the process of remediation of landfill site soil contaminated with leachate using material flow analysis

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A B S T R A C T

There are two possible cases concerning non-sanitary municipal solid waste landfills due to failure to meet requirements with respect to impermeability and thickness of geological barrier as well as absence of implementation and use of a waste and leachate management system, and also depending on type and the mineral composition of the geological barrier. In the first case, impermeable clay, kaolinite, is prevailing in the composition of the geological barrier the final outcome of which is the spillage of leachate into the volume of the deposited waste, as well as its outbreak on the surface of the landfill site. In the second case, permeable clay, smectite, is prevailing in the composition of geological barrier with dominant leachate infiltration into the ground flow. In accordance with the first case, using STAN software the substance flow analysis (SFA) was carried out, of cadmium primarily, within three scenarios. Efficacy of remediation of the landfill site soil contaminated with leachate from the aspect of heavy metal reduction, focused primarily on cadmium, using *in-situ* and *ex-situ* systems, was presented within Scenario 1 and Scenario 2. Possibility and efficacy of direct treatment of leachate in a corresponding plant for its processing, in case of implementing and using the leachate management system, was presented within Scenario 3. Efficacy of cadmium flow reduction accomplished within Scenario 1, Scenario 2 and Scenario 3 amounts to 99.04 %, 55 % and 99.2 %, respectively. Prevention of landfill site contamination with leachate using the system of its management is an optimum option and a desirable practice, while in the case of the already existing contamination of the landfill site and its immediate environment, using *in-situ* system of landfill site soil remediation, based on achieved results, high efficacy was achieved contrary to use of the *ex-situ* system.

1. Introduction

Contamination of a landfill site is a condition influenced by a complex of factors, before all the absence of or inadequate implementation and use of a waste and leachate management system. Non-sanitary municipal solid waste landfills are an optimum example of absence of implementation and use of both systems mentioned. Requirements pertaining to impermeability and thickness of natural geological barrier in the event of non-sanitary landfills were not met, whereby the absence of a system for collection and removal of leachate from the landfill

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body are additional aggravating and risky circumstances (Ministry of Environment, Mining and Spatial Planning, 2010; Karanac et al., 2015).

In such circumstances, the role of protective liner between the landfill body and the unsaturated area is performed by impermeable layer consisting of a combination of a geological barrier and a bottom liner of the landfill and a base which, considering its geological composition, consists of clay. Depending on mineral composition of clay, of which the base is made, there are two possible situations. If impermeable clay - kaolinite is present on the landfill site, infiltration of leachate of the landfill into the groundwater flow is the slightest possible, whereby the increase in the volume of filtrates in water storage within the landfill site is prevailing. After exceeding the capacity of water storage, leachate goes through constitutive layers of landfill site cells, if any, or they are discharged into the volume of the deposited waste. Therefore, leachate comes up to the surface of the landfill site causing it to collapse. Due to complex qualitative and quantitative composition of leachate, landfill site and its immediate environment become contaminated. In the second case, if clay, of which the base is made, falls into a group of permeable smectite according to its mineral composition, the occurrence of leachate infiltration into the groundwater flow will be prevailing. Tendency towards outcome of the first case is beyond any doubt, however its realization will take a longer period of time. Groundwater is a primary contaminated medium in the said case. Leachate is an entity influenced by a complex of factors, both within the very landfill body (landfill age, morphological composition of waste, temperature and content of moisture, migration flow of liquid, technology of waste treatment before disposal, thickness of the landfill body, waste decomposition stages) and outside of it (meteorological parameters, with a focus on annual precipitation, the seasons). The process of forming landfill filtrate comprises decomposition of solid substances in water being filtrated through the landfill body and the separation of dissolved or suspended matter incurred through biological and chemical processes inevitably taking place within the landfill body (Antić, 2016). Basic physical features characterizing landfill leachate are dark-brown colour of filtrate and intensive odour, while high level of pollutant concentration and the values of biological consumption of oxygen over the course of five days in the amount of 5,000 mg/l, represent their exemplary chemical parameters.

Pollutants represented in the composition of leachate of municipal landfills can be divided into four groups: soluble organic components, inorganic macrocomponents, heavy metals and xenobiotic organic components (Kjeldsen et al., 2002; Renou et al., 2008; Abbas et al., 2009; Bušatlić et al., 2017). Except for the mentioned four groups of components, other compounds and elements such as borate, sulphide, selenate, barium, lithium, mercury and cobalt (Kjeldsen et al., 2002) can also be identified within chemical composition of leachate. Due to complex qualitative composition of leachate, as a potential contaminant, Assessment of condition of the environment of a contaminated site as well as the creation of a Plan of recultivation, sanitation and remediation are deemed as necessary activities. Selection of adequate remediation technologies for treatment of landfill site soil contaminated by leachate is among last stages in the creation of the Plan, whereby aspiration towards separation of targeted pollutants, efficiency and price of remediation technologies are considered as primary factors.

Mediums of the environment contaminated with toxic heavy metal cadmium are a basic cause of harmful effects on the environment and on people's health as well due to its allocation in food chain. Harmful effects on people's health are varying and depend on intensity of exposure to cadmium concentrations. Cadmium poisoning symptoms are diarrhea, pain in stomach, nausea, while the consequences are reflected in the immune system disorders, sterility, possible DNA damage (Crichton, 2012). Cadmium is characterized by high bioconcentration factor (BCF) and therefore it is predominantly deposited in liver, kidneys and bones, causing bones to become more fragile with the possibility of osteoporosis. Several epidemiological studies have confirmed that the intake of cadmium is related to lung and prostate cancer, and recently it has been classified according to IARC as Group 1 carcinogen (Nodberg et al., 2007). Acute poisoning with cadmium can have a fatal outcome. A case of mass poisoning of population after consuming rice grown in the fields irrigated with river water contaminated with cadmium from industrial waste water of the nearby factory was recorded in Toyama prefecture of Japan in early 1912. Poisoning with toxic heavy metal cadmium was manifested in a disease called “Itai-itai”. Basic pathophysiological mechanism explaining toxicity of cadmium is enzyme inactivation via sulfhydryl (SH) groups. This way synthesis of hem (a haemoglobin component) is reduced and enzymes of significance for bone metabolism are inhibited. All this leads to demineralization of bones and to cadmium excretion through urine and also to “bone softening”, the so-called osteomalacia. In addition to this mechanism, cadmium also replaces calcium in bones; however since it does not have the same properties as calcium, bones become soft and fragile. The mentioned poisoning is accompanied with heavy pain which is why the disease was named “Itai-itai”, which means “It hurts-It hurts disease” (Nodberg et al., 2007).

Three scenarios were created in the paper the goal of which is to establish efficacy of heavy metal reduction, of cadmium before all. Efficacy of remediation of the landfill site soil contaminated with leachate, from the aspect of heavy metal reduction, with a focus on cadmium, using *in-situ* and *ex-situ* systems, is presented within Scenario 1 and Scenario 2. Due to high efficacy of heavy metal reduction and financial feasibility, two remediation technologies have been selected within the *in-situ* system - chemical oxidation and phytoremediation, whereas within the *ex-situ* system, soil washing and vitrification have been applied.

Possibility and efficacy of direct treatment of the landfill filtrate in the leachate treatment plant is presented within Scenario 3. The formed system represents an integration of conventional and alternative treatment methods, namely physical and chemical methods of coagulation/flocculation, biological treatment using membrane bioreactor with side flow and alternative tertiary treatment, using phytoremediation methods, with a goal of enhancing efficiency of heavy metal flow reduction. After achieving these results it will be concluded whether the direct treatment of landfill filtrate within the leachate treatment plant represents an optimum prevention of landfill site soil contamination, namely whether it is necessary to implement and apply the leachate management system. Also, in case of the already contaminated landfill site soil, comparison of the efficacy of the reduction of cadmium flow will be carried out within Scenarios 1 and 2, namely within *in-situ* and *ex-situ* remediation system.

2. Methods

By analysing the flows of material using STAN software, the substance flow analysis (SFA) was carried out, of cadmium before all, within three scenarios (Brunner and Rechberger, 2004; Cencic and Rechberger, 2008; Stanisavljevic and Brunner, 2014).

2.1. Development of Scenario 1

In-situ treatment of landfill site soil contaminated with leachate is presented within Scenario 1. The selected technologies, chemical oxidation and phytoremediation, were selected due to high efficacy of the reduction of heavy metal flows and economic feasibility.

The use of a method of chemical oxidation presupposes construction works within the landfill body, with a goal of installing injection, extraction and observation well. Oxidation agent, most typically it is H_2O_2, is inserted in the contaminated soil through an injection well, while the remaining oxidation agent, with accumulated congeners of toxic pollutants from contaminated soil is extracted through an extraction well. Extracted oxidant is treated in the plant for recovery of oxidation agent with a goal to repeat the use within the mentioned process. Also, within the mentioned plant toxic congeners accumulated in the oxidation agent are being deposited within the *in-situ* process of chemical oxidation, after which the formed deposit is extracted from the system. The process of chemical oxidation is shown in Figure 1. By applying the mentioned process an efficient treatment of deep layers of contaminated soil is achieved and, if necessary, of contaminated groundwater as well.

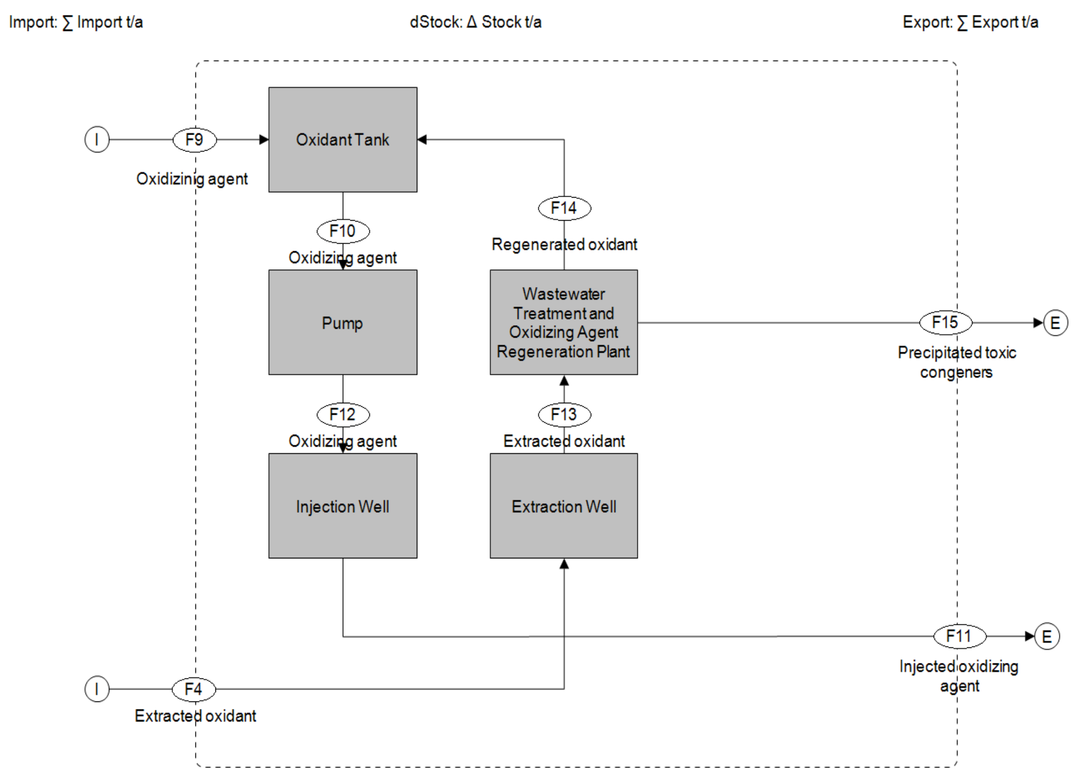

Figure 1. *In-situ* process of chemical oxidation implemented within contaminated landfill site

Phytoremediation method represents another selected technology for the treatment of contaminated landfill site soil. High efficacy in the reduction of heavy metal concentration in surface layers of contaminated soil is achieved by implementing hyperaccumulating biomass, such as *Typha domingensis*, *Brassica napus* and *Typha latifolia L*. After applying this method, heavy metals accumulated within waste biomass are extracted from the system, whereby they can be applied in cement plants in the form of alternative fuel or in the form of hazardous waste they can be forwarded to an operator for further handling and treatment. The benefit of applying the said method is in short-term enhancement of an aesthetic aspect of the treated landfill site.

Overview of the entire *in-situ* system for the treatment of landfill site soil contaminated with leachate is shown in Figure 2.

By applying the mentioned *in-situ* treatment of landfill site soil contaminated with leachate allows a full-scale treatment of both deep and surface layers of contaminated soil. Implementation of the said system is recommended primarily for municipal solid waste landfills within which a voluminous scattered contamination of soil with heavy metals and with xenobiotic organic compounds as well was identified through Assessment of the condition of the environment.

2.2. Development of Scenario 2

Ex-situ treatment of landfill site soil contaminated with leachate is presented within Scenario 2. Soil washing and *ex-situ* variation of the vitrification method were selected due to high efficacy of the reduction of heavy metal concentration and exceptional efficiency. Optimum efficient reduction of the concentration of heavy metals in surface layers of contaminated soil is performed by applying the method of soil washing. Soil allocated through the process of excavation is treated outside the landfill site whereby reducing potential risks to people's health and environment, while at the same time incurring substantial financial transportation costs, as well as negative aspects of applying the mentioned method. Final products of the said treatment are filtered water, which can be used within the treatment plant as a technical fluid or it can be drained into a water-receptor, and treated soil which is in practice normally returned to the landfill site.

Treatment of coarse fractions of treated soil as well as of heavy metal flows within produced vitrified soil is

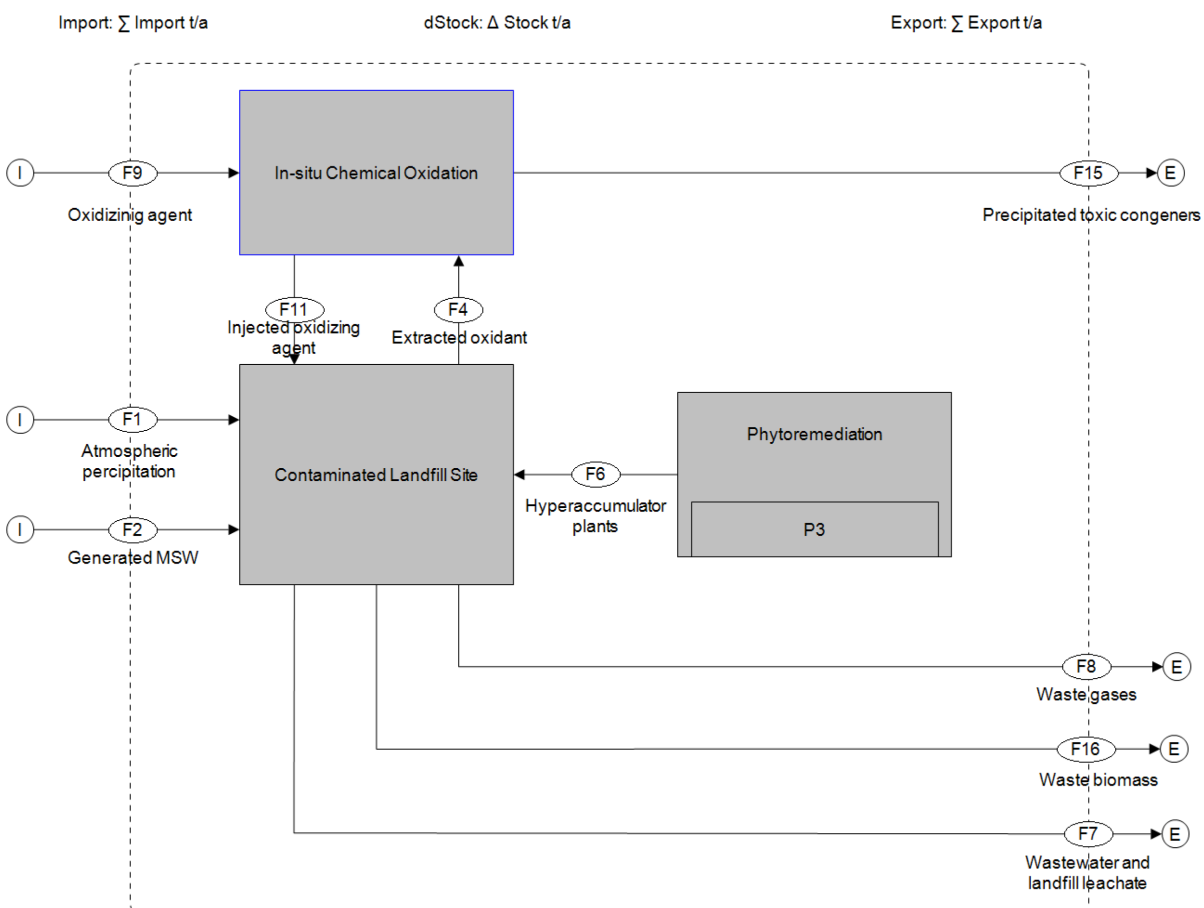

Figure 2. *In-situ* treatment of landfill site soil contaminated with leachate

carried out using vitrification method. Final products of the said method are vitrified soil and waste gases. The incurred vitrified mass is of great strength and it is resistant to the leaching of pollutants trapped in it which are therefore prevented from melting and migration into groundwater or any other possible impact on the environment. In practice, vitrified soil typically returns to the landfill site or, as a hazardous waste, it is further treated by operator. The system of *ex-situ* treatment of landfill site soil contaminated with leachate is shown in Figure 3 while *ex-situ* processes of soil washing and vitrification are shown in Figure 4 and Figure 5.

The application of the presented *ex-situ* system of treatment of landfill site soil contaminated with leachate is recommended primarily in case of concentrated pollution of surface layers of landfill site soil with heavy metals.

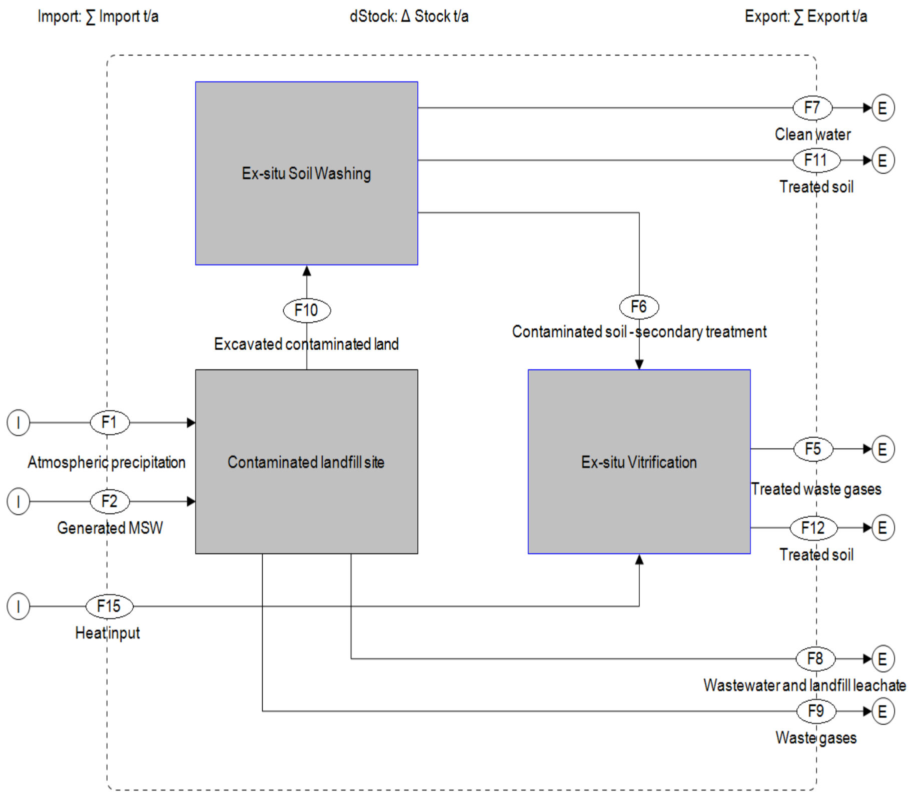

Figure 3. *Ex-situ* treatment of landfill site soil contaminated with leachate

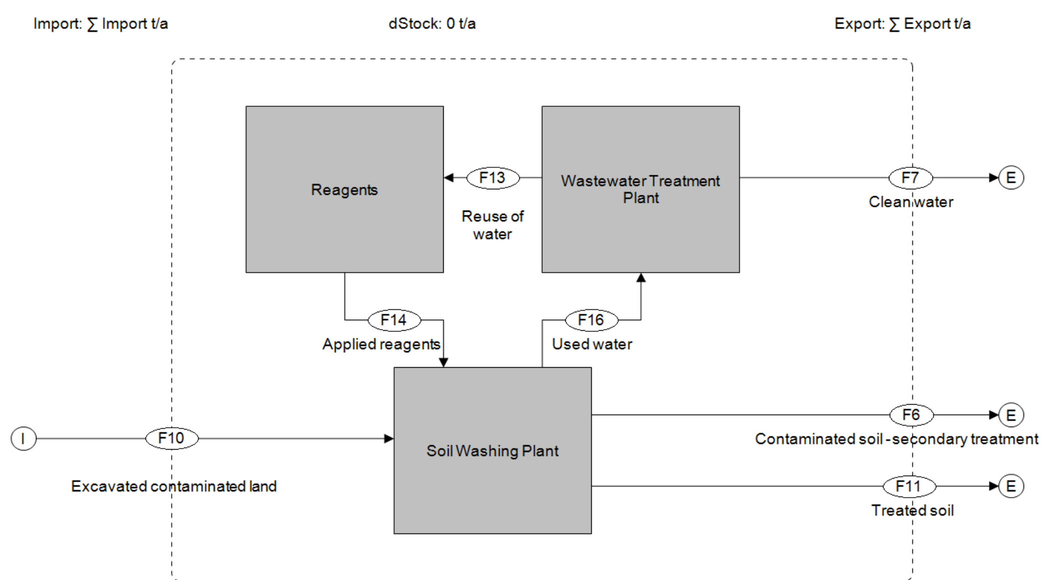

Figure 4. Overview of *ex-situ* process of washing soil of contaminated landfill site

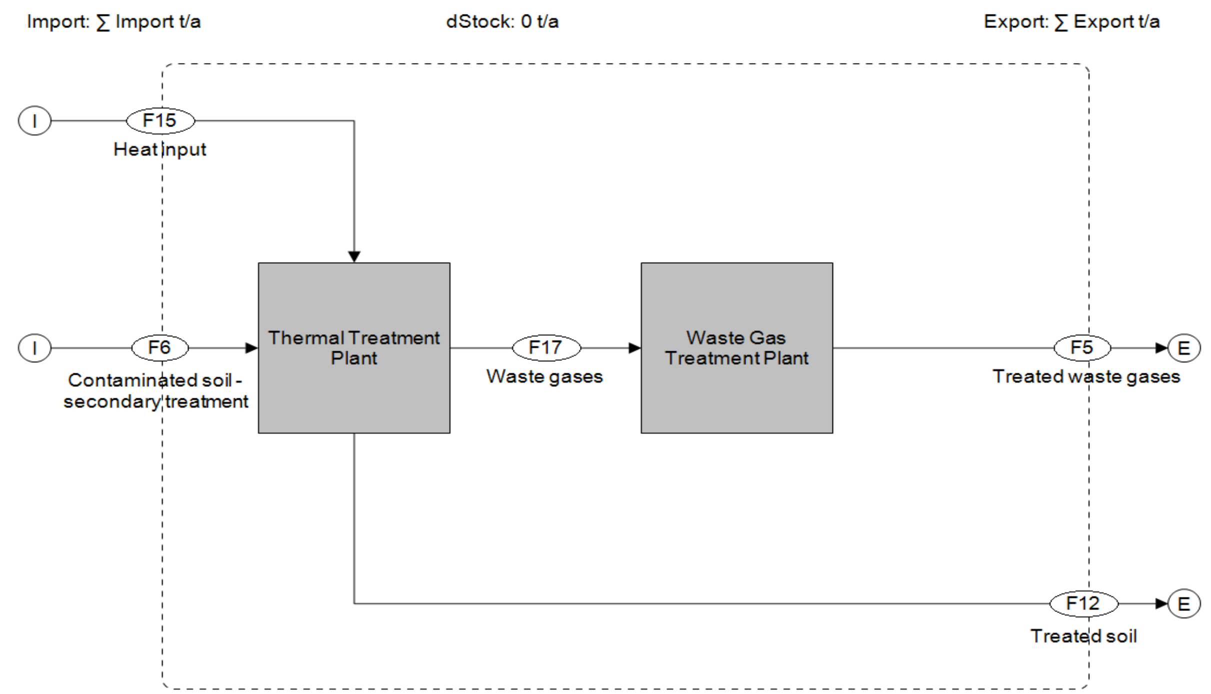

Figure 5. Overview of *ex-situ* process of vitrification as a secondary treatment of coarse fractions retained after the process of soil washing

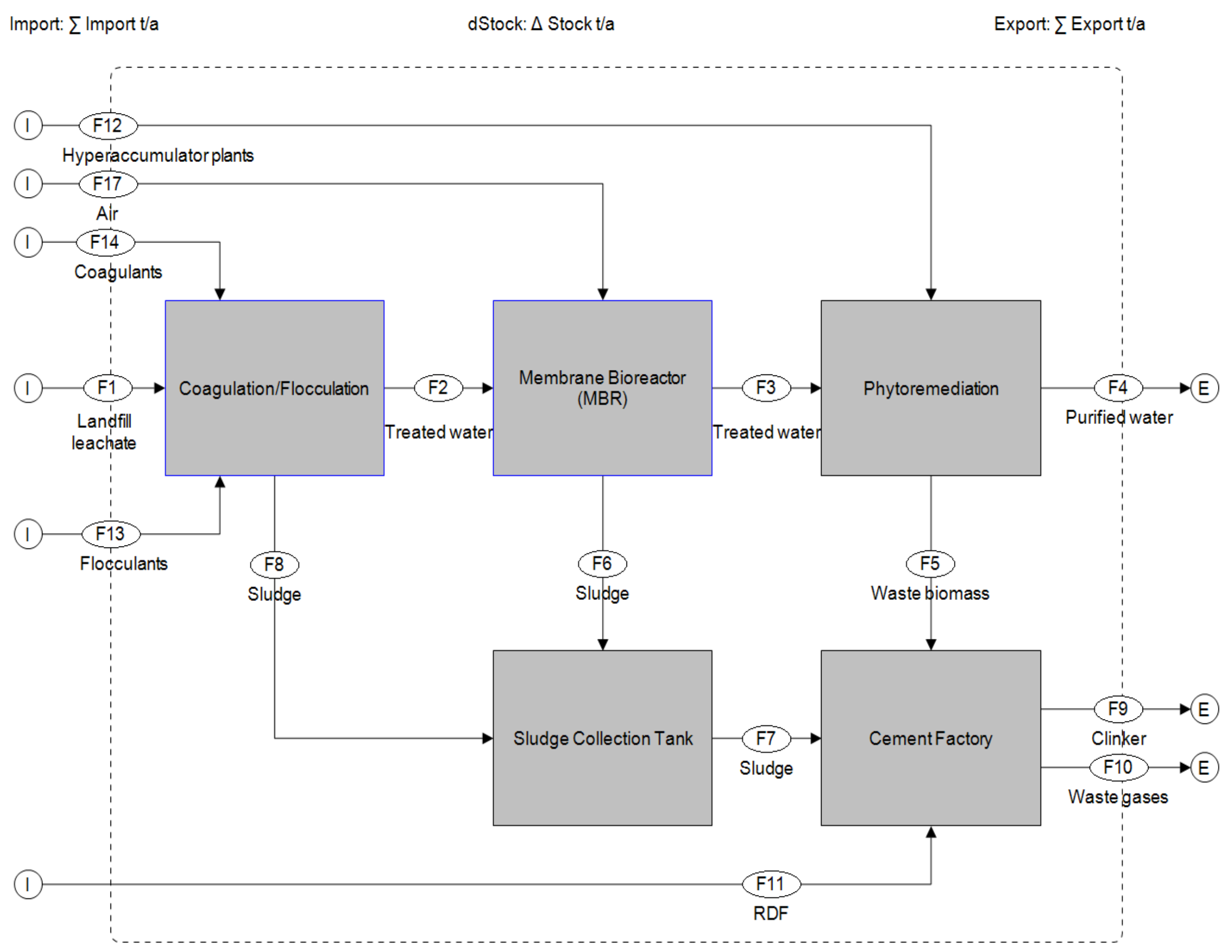

Figure 6. Model of a landfill leachate treatment plant

2.3. Development of Scenario 3

Figure 6 shows treatment of landfill filtrate within the leachate treatment plant. The shown system represents an integration of conventional and alternative treatment methods, namely physical and chemical methods of coagulation/flocculation, biological treatment by applying membrane bioreactor with side flow and alternative tertiary treatment by applying the method of phytoremediation, with aim to improve efficacy of the reduction of heavy metal concentration.

The process of applying coagulation/flocculation treatment is shown in Figure 7 whereas the implementation of the method of membrane bioreactors is shown in Figure 8.

The line of sludge incurred within physical and chemical process of coagulation/flocculation and of applying biological MBR process is collected in the sludge collecting tank. Collected sludge and waste biomass from the process of phytoremediation can be efficiently treated at cement plants if concentrations of heavy metals in waste products do not exceed prescribed limits in alternative fuels suitable for use in cement plants.

2.4. Applied data

Data applied for determining the input flow of cadmium within Scenarios 1 and 2 are represented as a generated volume of solid municipal waste in the municipality of Novi Sad, which amounts to 133,104 kg/year and a mass percentage of cadmium within the solid municipal waste stream, which amounts to 11 mg/kg (Korzun and Heck, 1990; Vujić et al., 2009a).

When calculating daily and annual volumes of generated leachate within Scenario 3, the following formula (1) applies (Miloradov, 2006):

$$Q_f = \frac{k \cdot (P + Q)}{365} \qquad (1)$$

where:

- Q_f - daily volume of filtrate [m^3/day],
- k - coefficient characterized by ability to absorb moisture and evaporation of waste,
- P - total annual volume of precipitation on the surface of waste [m^3/year],
- Q - total annual volume of water distributed on the surface of waste [m^3/year],
- F - surface [ha].

Data applied when calculating daily and annual volumes of generated leachate come from real sources. The data referring to the surface of a hypothetical landfill site has been projected on the basis of real data of exploited surface of landfill site “City Landfill” Novi Sad and amounts to 35,381 m^2, while the annual volume of precipitation was measured on the level of synoptic station Novi Sad in the period between 1981 and 2010

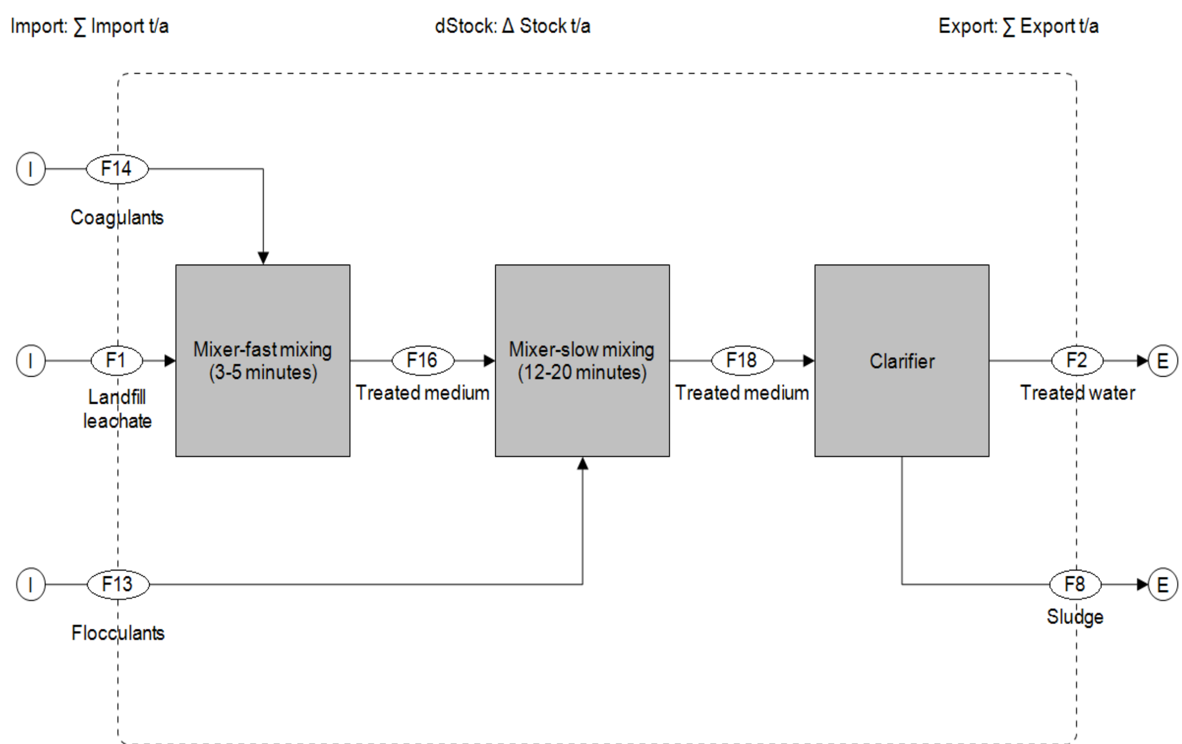

Figure 7. Implementation of physical and chemical method of coagulation/flocculation within the landfill leachate treatment plant

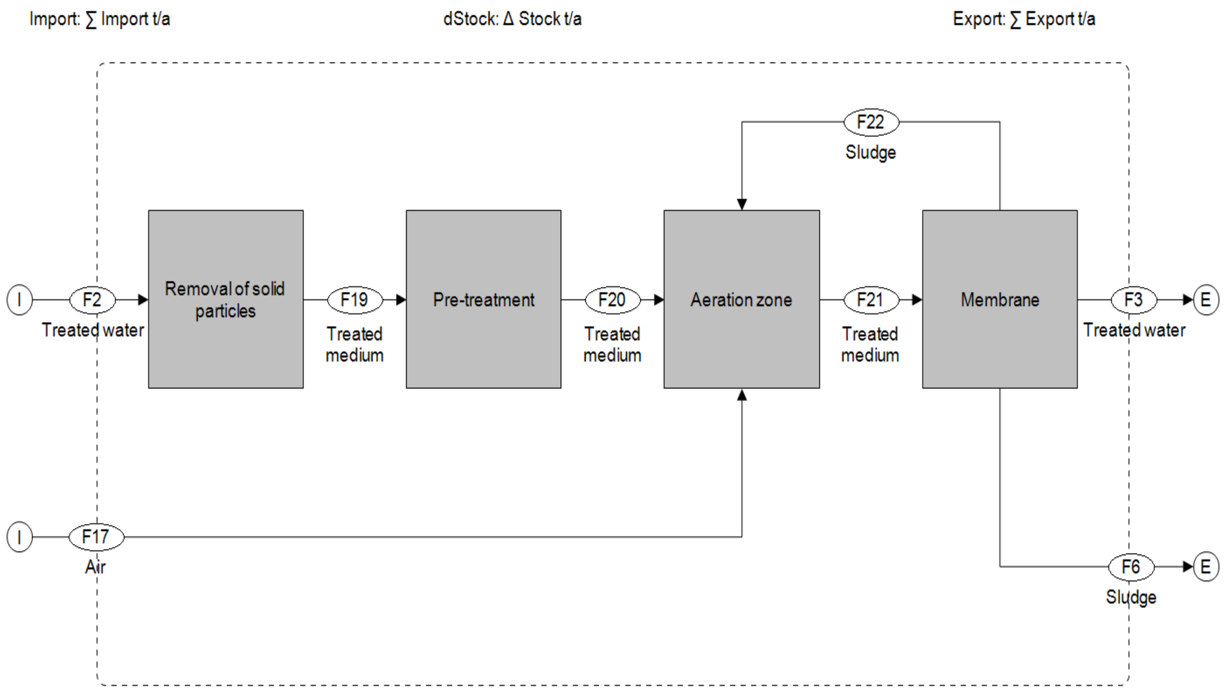

Figure 8. Implementation of biological method of membrane bioreactor with side flow

and it amounts to 647.3 mm/year (Vujić et al., 2009a; Republic Hydrometeorological Service of Serbia, 2010).

When applying the methodology it is necessary to take into consideration the fact that 70 % of precipitation evaporates from the landfill through drying, and 25 % evaporates through biometric processers occurring in the layer of deposited waste at depth of 0.5 to 2 m. Remaining precipitation, as a filtrate, migrates down to the bottom of the landfill by 5-15 % for a sloped area and by 1-10 % for the area which is not sloped. Consequently, the coefficient k for landfill sites on a flat terrain amounts to 0.1, while for sloped landfill sites (mostly 2 %) it amounts to 0.15 (Miloradov, 2006). Also, the total annual volume of water distributed on the surface of waste actually accounts for merely 30 % of total annual precipitation left after evaporation off the landfill site surface.

In calculations the formula (2) applies for conversion of values from the level of mm/year to m^3/year (Berndtsson et al., 2014):

$$mm/year = \frac{10^{-3} m^3}{1\ m^2} year \quad (2)$$

By applying the said formula (2) we have concluded that the annual volume of precipitation per 1 m^2 amounts to 0.6473 m^3. Introducing exploited area of the landfill site “City Landfill” Novi Sad which amounts to 35,381 m^2, we have calculated that the annual volume of precipitation for the given surface amounts to 22,902.12 m^3/year. Therefore, a factor P was determined within the formula (1). On the basis of the obtained results, the factor Q was calculated and it represents the remaining 30 % of total annual precipitation distributed on the surface of waste and it amounts to 6,870.64 m^3/year. On the basis of the presented data an assessment of generating leachate was carried out within the hypothetical landfill site, on a daily (3) and on an annual (4) basis.

$$Q_f = \frac{0.15 \cdot (22{,}902.1213\ m^3/year\ + 6{,}870.63639\ m^3/year)}{365} = 12.24\ m^3\ /year \quad (3)$$

$$Q_f = 0.15 \cdot (22{,}902.1213\ m^3/year\ + 6{,}870.63639\ m^3/\ year) = 4{,}465.914\ m^3/year \quad (4)$$

Concentration of cadmium within the generated volume of leachate was established on the basis of field testing and qualitative analysis of leachate from the landfill site “City Landfill” in Novi Sad. Values of the stated concentration amount to 0.02 mg/L, and 20 mg/m^3 (Vujić et al., 2009b).

Within the *in-situ* system of Scenario 1, the value of efficacy of the reduction of the flow of cadmium through the method of chemical oxidation was adopted on the basis of book values, by applying H_2O_2 as an oxidizing agent, and it amounts to 95 %, while through the method of phytoremediation using plant species *Typha* *domingensis*, *Brassica napus* and *Typha latifolia L.*, amounts to 81 % (Seol and Javandel, 2008; Lavagnolo et al., 2016; Mojiri et al., 2016; Antić et al., 2017; Ferniza-García et al., 2017).

Within the *ex-situ* system of Scenario 2, and based on book values, the value of efficacy of the reduction of the flow of cadmium through the method of soil washing amounts to 55 %, while through the method of vitrification, executed while performing field testing amounts to 70 % (Thompson et al., 1992; Kos and Leštan, 2003; Pociecha et al., 2011; Sung et al., 2011).

Within Scenario 3, the value of efficacy of the reduction of the cadmium flow by applying the method of coagulation/flocculation is ranging between 74 % (field research) to 98 % (laboratory research) (Kurniawan, 2011). For the purpose of Scenario 3, efficacy of the method in the amount of 74 %, established on the basis of field research, was adopted. Efficacy of the reduction of cadmium flow within MBR plant was adopted on the basis of book value and amounts to 84 % (Mahmoudkhani, 2014). Efficacy of the reduction of cadmium flow by applying the phytoremediation method was tested experimentally several times by experts. It was established that efficacy amounting to 81 % was achieved by using plant species *Typha domingensis*, *Eichhornia crassipes* and *Typha latifolia L.* (Mojiri et al., 2016; Antić et al., 2017; Ferniza-García et al., 2017). Within the treatment at the cement plant, 99.98 % of the flow of cadmium was concentrated in clinkers, and the remaining 0.02 % through waste gases are emitted in the environment (Korzun and Heck, 1990; Mitchell et al., 1992).

3. Results and discussion

3.1. Scenario 1

Due to possibly very harmful impact on the environment and people's health, within Scenario 1, the focus is on efficacy of the reduction of the flow of toxic heavy metal cadmium on the level of landfill site soil contaminated with leachate.

The flow of cadmium in remediation of the landfill site soil contaminated with leachate on an annual basis is shown in Figure 9.

The input flow of cadmium was concentrated within generated waste deposited on the landfill site in the amount of 1,464,144 g/year, and 1,464.14 kg/year. Cadmium concentrations were not recorded in remaining input flows, i.e. precipitation and heat input.

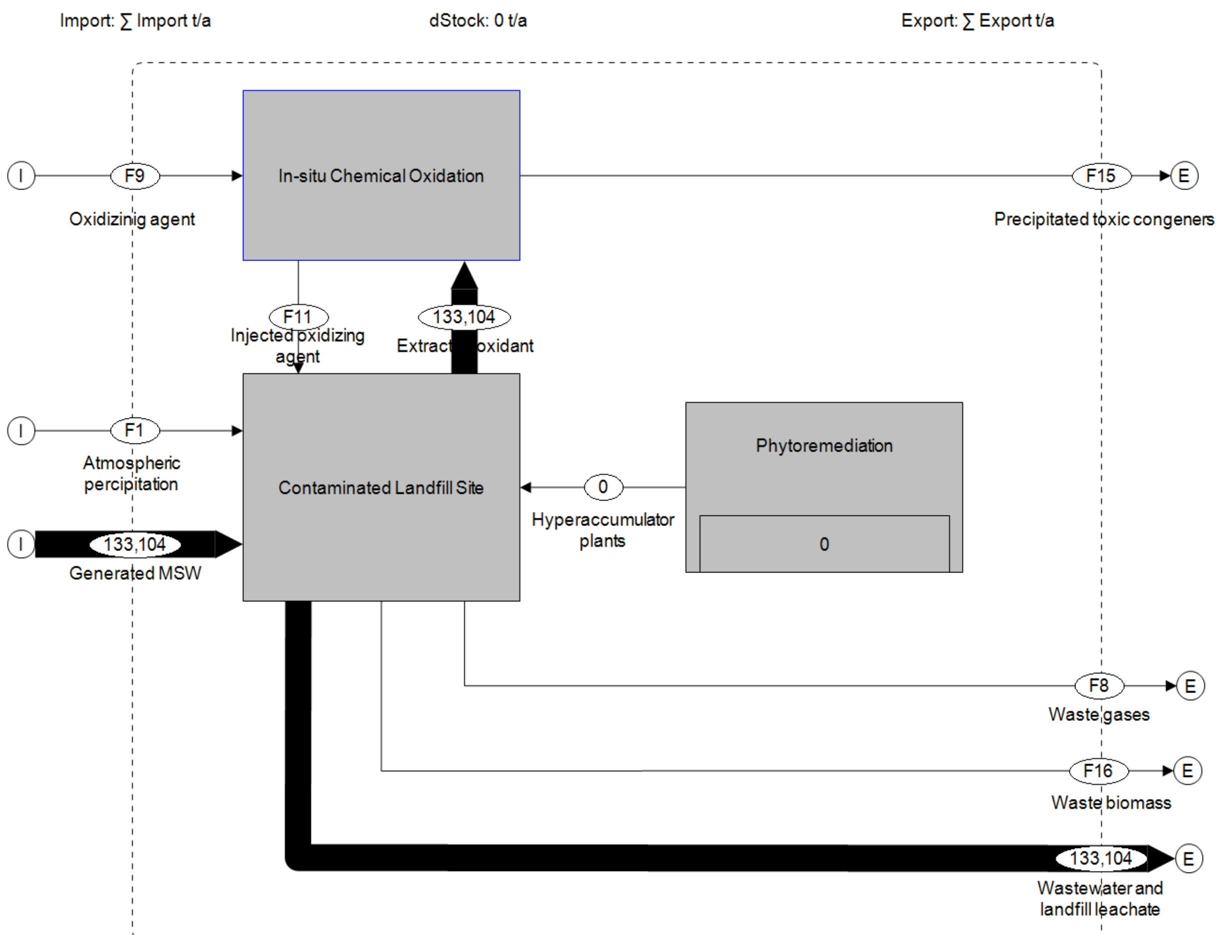

Figure 9. The flow of cadmium within the process of *in-situ* remediation of landfill site soil contaminated with leachate (g/year)

Efficacy of the *in-situ* method of chemical oxidation was adopted on the basis of book data and amounts to 95 % (Seol and Javandel, 2008). Accordingly, 95 % of the initial cadmium flow, namely 1,390,937 g/year or 1,390.94 kg/year, was accumulated and extracted in the form of toxic congeners of cadmium together with the remaining oxidizing agent. The flow of cadmium within the *in-situ* method of chemical oxidation is shown in Figure 10.

After performed *in-situ* chemical oxidation treatment, 5 % of the initial flow of cadmium remains within the landfill site soil contaminated with leachate, primarily in surface layers. Secondary treatment of contaminated soil is carried out by applying the method of phytoremediation using plant species Typha domingensis, Brassica napus and Typha latifolia L. Efficacy of the reduction of the flow of cadmium by applying the method of phytoremediation using the mentioned plant species was adopted on the basis of recorded data and amounts to 81 % (Lavagnolo et al., 2016; Mojiri et al., 2016; Antić et al., 2017; Ferniza-García et al., 2017).

Accordingly, after implementing the method of phytoremediation within the waste mass, 4.05 % of the remaining flow of cadmium is being accumulated, namely 59,298 g/year or 59.3 kg/year. The remaining 0.95 % of the flow of cadmium, namely 13,909 g/year or 13.91 kg/year, through leachate generated within the landfill site is allocated to groundwater aquifer.

Based on the flow of cadmium shown in Figure 4 and the performed calculations, it has been established that the efficacy of the applied *in-situ* methods of soil remediation at the landfill site contaminated with leachate amounts to 99.04 %.

3.2. Scenario 2

Due to possibly very harmful impact on the environment and people's health, the focus within Scenario 2 is on the efficacy of the reduction of the flow of toxic heavy metal cadmium on the level of the landfill site soil contaminated with leachate waters. The flow of cadmium within the remediation of landfill site soil contaminated with leachate on an annual basis is shown in Figure 11.

The input flow of cadmium is concentrated in generated waste deposited on the landfill site and it amounts to 11 mg/kg, whereby the annual flow of cadmium within the municipal waste was obtained and it amounts to 1,464,144 g/year, i.e. 1,464.14 kg/year. Cadmium concentrations were not recorded in remaining input flows, namely precipitation and heat input.

Considering the mechanism of leachate production, in

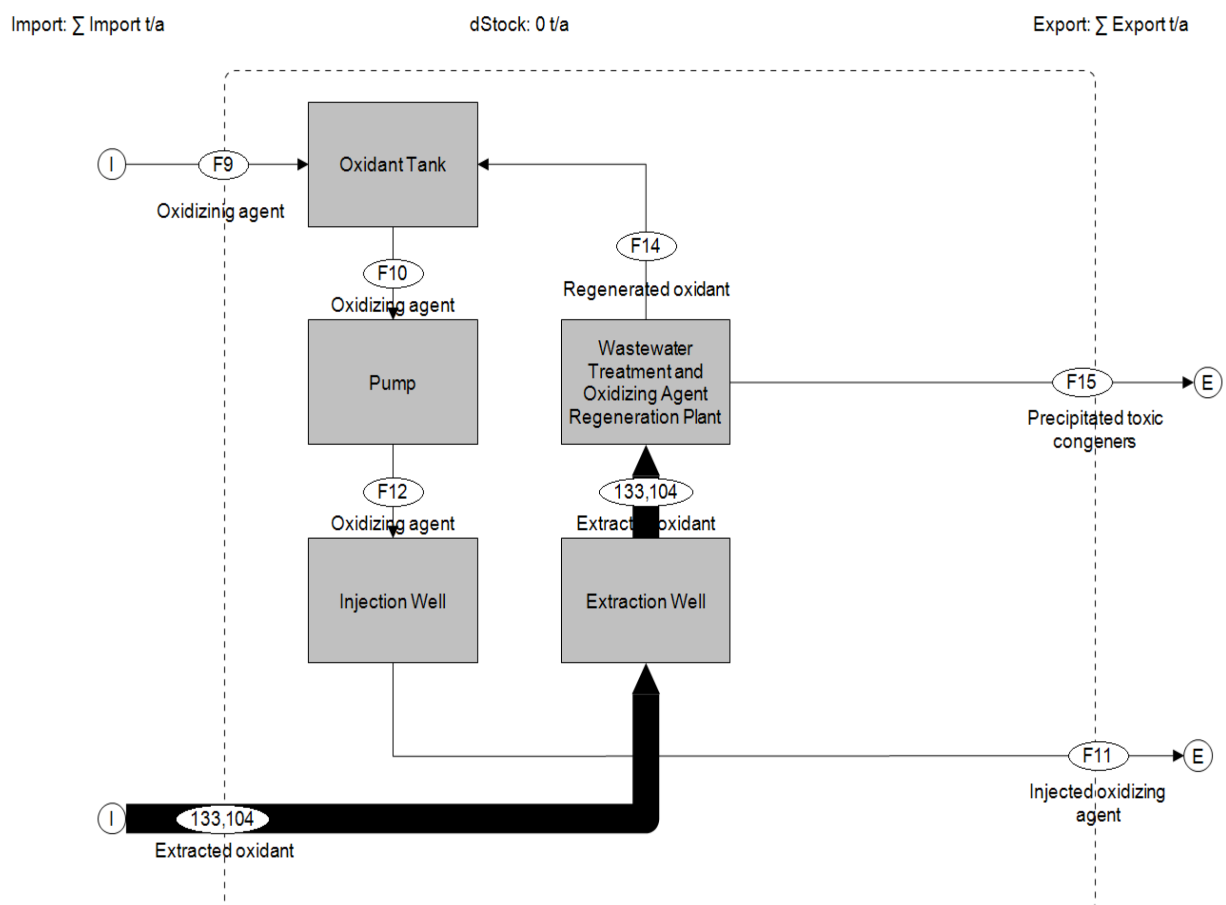

Figure 10. The flow of cadmium within *in-situ* treatment of chemical oxidation of the landfill site soil contaminated with leachate (g/year)

the event of non-sanitary municipal solid waste landfills without the system for its removal and collection, 85 % of cadmium concentration contaminates soil on and in the vicinity of the landfill site through leachate as a transfer medium discharged onto the surface of the landfill site. The mass flow rate within the said stream amounts to 1,244,522 g/year, i.e. 1,244.52 kg/year. Within the landfill body, with potential for collecting and/or infiltration in groundwater aquifer only 5-15 % of the landfill filtrate remains, carrying with it 15 % of the initially generated concentration of cadmium, namely 219,622 g/year or 219.62 kg/year (Miloradov, 2006).

Value of efficacy of the reduction of cadmium concentration by applying *ex-situ* method of washing soil was adopted on the basis of book data, namely the value of efficacy of the reduction of heavy metals achieved through field testing, which amounts to 55 % was applied (Kos and Leštan, 2003; Pociecha et al., 2011; Sung et al., 2011). Accordingly, after implementation and execution of the said treatment, treated land and clean water are obtained as final products. The treated land usually in practice returns to the landfill site carrying with it 45 % of the initial cadmium flow from the treated medium, namely 560,035 g/year or 560.04 kg/year, while the remaining 55 % of cadmium flow, namely 684,487 g/year or 684.49 kg/year, is stored within coarse fractions of soil which are not subject to the applied treatment.

Coarse fraction of contaminated soil which is not subject to *ex-situ* treatment of land washing, within which the flow of cadmium amounts to 684,487 g/year, namely 684.49 kg/year, is sent for *ex-situ* vitrification treatment. The value of efficacy of the reduction of cadmium concentration by applying *ex-situ* vitrification method was adopted on the basis of book data, namely the value of efficacy of the reduction of heavy metals obtained through field testing was applied, which amounts to 70 % (Thompson et al., 1992).

After performing the treatment on vitrified soil the flow of cadmium amounts to 479,141 g/year, namely 479.14 kg/year. Disadvantage of the said treatment is the necessity to perform multi-stage filtering of waste gases. In practice, conditions for the required level of clearing of waste gases typically do not exist, and so the remaining 30 % of cadmium flow, namely 205,346 g/year or 205.35 kg/year are either directly or indirectly emitted in environment.

On the basis of the flow of cadmium shown in Figure 11 and calculations performed, it has been established that efficacy of the applied *ex-situ* methods of remediation treatment of landfill site soil contaminated with leachate amounts to 55 %. The advantage of the presented system is permanent conservation and fixation of 70 % of the flow of cadmium present in coarse fraction of contaminated soil treated by *ex-situ* vitrification

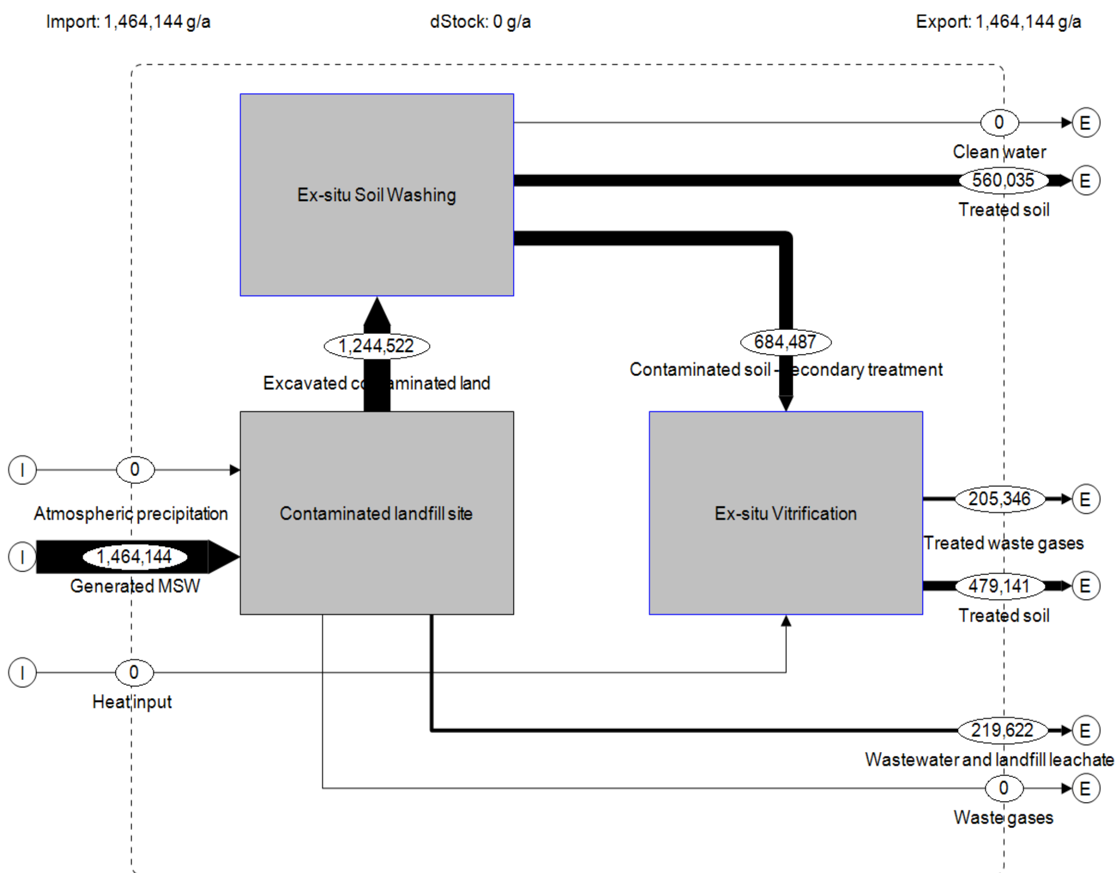

Figure 11. Flow of cadmium within *ex-situ* remediation of landfill site soil contaminated with leachate (g/year)

method. For the purpose of improving the end quality of soil which is after applying *ex-situ* washing process returned to the landfill site, it is necessary to apply additional treatment of the said fraction. Optimum selection in achieving the said goal is thermal treatments, such as pyrolysis or incineration, characterized by high range of efficacy of the reduction of heavy metals, from 93.91 % to 99.9 %, within the treated medium (Debela et al., 2012; US Environmental Protection Agency, 2012).

Long-term financially sustainable option for improving the quality of soil which, after the process of *ex-situ* washing returns to the landfill site, as well as simultaneously long-term maintenance of the quality of surface layers of soil of the landfill site, is the implementation of the method of phytoremediation using wooden plant species such as black alder (*Alnus glutinosa*), silver birch (*Betula pendula*) and black pine (*Pinus nigra*). The use of trees within the phytoremediation method may result in extraction of substantial quantities of metal, due to their high production of biomass. Also, the advantage of implementing the said method is the forming of a new sustainable ecosystem and the green belt, as well as the aesthetic enhancement of the treated site.

3.3. Scenario 3

Due to a possibly very harmful impact on the environment and people's health, within Scenario 3 the focus of attention is on the efficacy of the reduction of concentrations of toxic heavy metal cadmium on the level of generated leachate, removed within sanitary municipal solid waste landfills through implementation and application of systems for collecting leachate.

The flow of cadmium within physical and chemical, biological and alternative treatment of leachate from solid waste municipal landfills on the level of a plant for treatment of leachate is shown in Figure 12.

Cadmium concentration within generated volume of leachate was determined on the basis of field testing and qualitative analysis of leachate from landfill sites of the "City Landfill" in Novi Sad. Values of the stated concentration amount to 0.02 mg/L, namely 20 mg/m3, on the basis of which the input mass flow of cadmium was calculated in leachate which amounts to 89,318 mg/year, and 89.32 g/year.

Efficacy of reduction of heavy metals by applying the method of coagulation/flocculation is ranging from 74 (based on field testing) to 98 % (based on laboratory

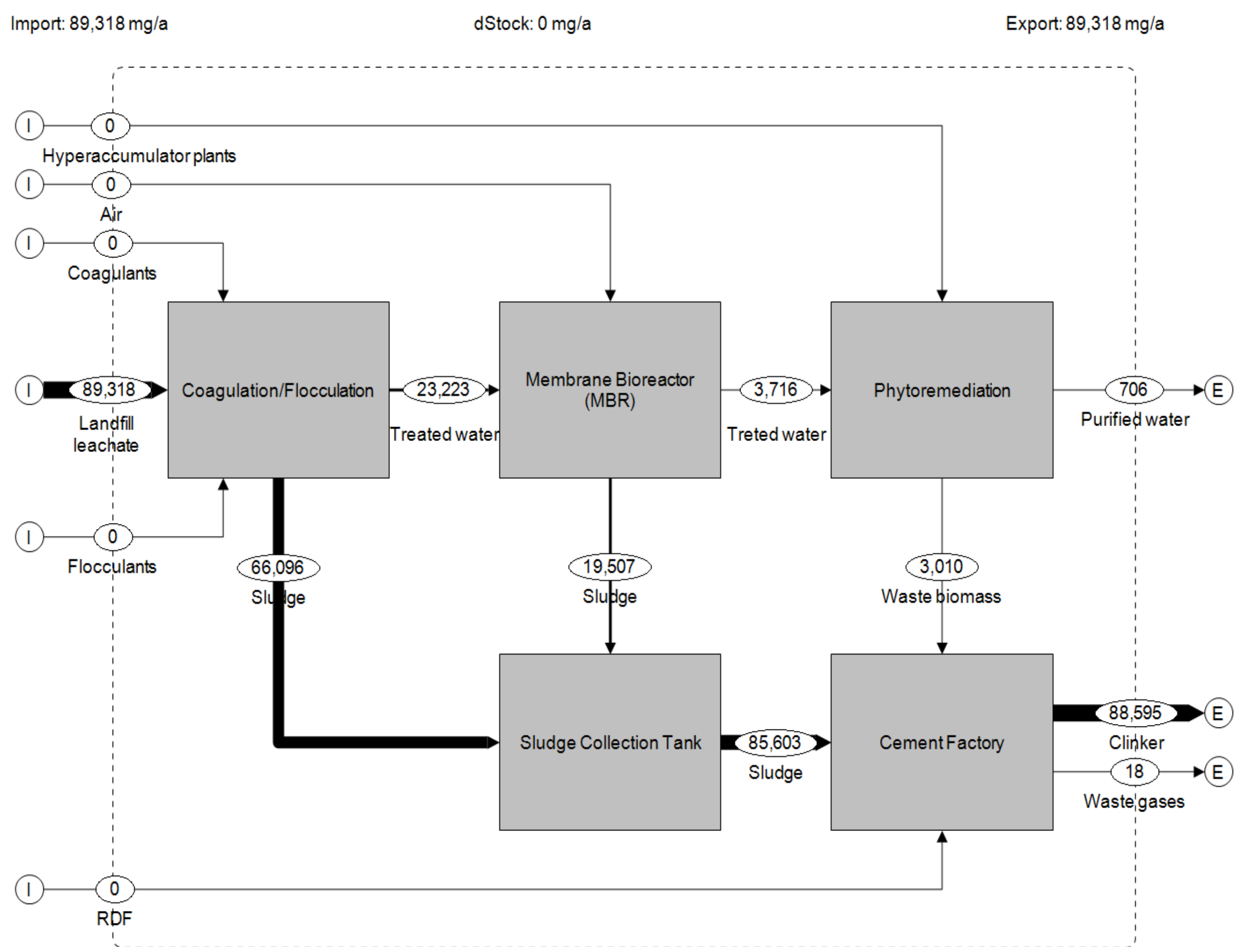

Figure 12. The flow of cadmium within the process of filtering leachate from municipal solid waste landfills in an adequate plant for physical and chemical, biological and alternative treatment (mg/year)

testing) (Kurniawan, 2011). In order to meet requirements of Scenario 3, the efficacy of the method in the amount of 74 %, established on the basis of field research, was adopted. Accordingly, 74 % of cadmium flow is deposited within waste sludge, whereby the flow of cadmium in this amounts to 66,096 mg/year, i.e. 66.096 g/year.

In leachate treated by applying the method of coagulation/flocculation, 26 % of the flow of cadmium remains, so the mass flow of cadmium within the stated stream amounts to 23,223 mg/year, i.e. 23.22 g/year.

Efficacy of cadmium reduction within MBR plant was adopted on the basis of a book value and it amounts to 84 % (Mahmoudkhani et al., 2014). Accordingly, 84 % of cadmium flow from previously treated leachate is concentrated in waste sludge, whereby the flow of cadmium in it amounts to 19,507 mg/year, i.e. 19.5 g/year. 16 % of cadmium flow remains in the secondary treated leachate, so the mass flow of cadmium in the said stream amounts to 3,716 mg/year, i.e. 3.72 g/year.

Efficacy of the reduction of cadmium by applying the method of phytoremediation was tested on several occasions experimentally by experts and it was concluded that efficacy in the amount of 81 % was achieved by using plant species *Typha domingensis*, *Eichhornia crassipes* and *Typha latifolia L*. (Mojiri et al., 2016; Antić et al., 2017; Ferniza-García et al., 2017). On the basis of the said above, 81 % of cadmium from secondary treated leachate is accumulated in biomass applied within the process of phytoremediation, whereby the mass flow of cadmium after the process of phytoremediation in waste biomass amounts to 3,010 mg/year, namely 3.01 g/year. 19 % of cadmium flow remains in tertiary leachate against the influent of tertiary treatment, so the flow of cadmium in leachate after applying the phytoremediation method amounts to 706 mg/year, i.e. 0.71 g/year.

It is possible to use sludge deposited in the tank for sludge storing, as well as waste biomass from tertiary treatment, and/or the process of phytoremediation, as alternative fuel in cement plants. For the purpose of presenting the flow of cadmium in the stated alternative fuels, Scenario 3 does not include the values of cadmium concentration within RDF, and/or primarily exploited fuel in cement plants. On the basis of book values, it is known that 99.98 % of the flow of cadmium is installed in the final product of cement plants, clinkers, while merely 0.02 % of cadmium flow is emitted within waste gases. Expressed in the form of a mass flow, 88,595 mg/year, i.e. 88.6 g/year of cadmium is installed in a clinker, while 18 mg/year, i.e. 0.02 g/year of cadmium is emitted within waste gases from cement plants.

On the basis of the flow of cadmium shown in Figure 12 and calculations performed, it has been concluded that the efficacy of the designed plant for leachate treatment within Scenario 3, including implemented primary - physical and chemical, secondary - biological and tertiary - alternative treatment, amounts to 99.2 % on an annual basis.

4. Conclusion

This paper demonstrates three possible Scenarios for soil remediation of contaminated landfill site, as well as direct treatment of the polluting medium, leachate. *In-situ* treatment of soil of the landfill site contaminated with leachate, shown within Scenario 1, enables a comprehensive treatment of both deep and surface layers of contaminated soil, so the implementation of the mentioned system is recommended primarily at solid waste municipal landfills within which a spacious scattered contamination with heavy metals and with xenobiotic organic compounds was determined through implementation of the Assessment of the condition of the environment. The use of the *ex-situ* system of treating landfill site soil contaminated with leachate, presented within Scenario 2, is recommended primarily in case of concentrated pollution of surface layers of landfill site soil with heavy metals. Treatment of landfill filtrate within the leachate treatment plant is presented within Scenario 3. The shown system represents integration of conventional and alternative treatment methods, namely physical and chemical methods of coagulation/flocculation, biological treatment by applying membrane bioreactor with side flow, and alternative tertiary treatment by using the method of phytoremediation, for the purpose of enhancing efficacy of reduction of heavy metal concentration.

On the basis of the presented cadmium flows and performed calculations, it has been concluded that efficacy of the applied *in-situ* system of treating remediation of landfill site soil contaminated with leachate amounts to 99.04 %, while *ex-situ* system of treatment amounts to 55 %, with the possibility for improving the performances by applying additional thermal and alternative treatments. Efficacy of the reduction of cadmium flow of the projected leachate filtering plant within Scenario 3, with implemented primary - physical and chemical, secondary - biological, and tertiary - alternative treatment, amounts to 99.2 % on an annual basis. The use of a method of collecting and filtering leachate is very suitable and optimal with aim to prevent the overflowing of contamination of the landfill site soil with leachate, as well as maintenance of optimum qualitative composition of generated landfill filtrate.

The models of applying remediationtechnologies as well as the very creation of the Plan for sanitation and remediation of contaminated sites vary depending on a particular case, considering the fact that certain specific factors characterize each landfill site in particular the effects of which either directly or indirectly affect the entire process of remediation of contaminated landfill site. The realization of the research has proven that the treatment of the landfill filtrate within the landfill leachate treatment plant is an essential step in the implementation of landfill leachate management system within the solid waste municipal landfills. Also, the above procedure represents an adequate measure of prevention from contamination of landfill site soil.

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Analiza efikasnosti procesa remedijacije zemljišta deponijskog lokaliteta kontaminiranog procednim vodama primenom analize tokova materijala

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I Z V O D

Kod nesanitarnih komunalnih deponija čvrstog otpada, usled nezadovoljavanja zahteva u pogledu vodonepropusnosti i debljine geološke barijere i odsustva implementacije i primene sistema za upravljanje otpadom i procednim vodama, kao i u zavisnosti od vrste i minerološkog sastava geološke barijere, moguća su dva slučaja. Pri prvom slučaju, u okviru sastava geološke barijere dominira nepropusna glina, kaolinit, te krajnji ishod predstavlja izlivanje procednih voda u zapreminu deponovanog otpada, kao i izbijanje istih na površinu deponijskog lokaliteta. Pri drugom slučaju, propusne gline, smektiti, preovlađuju u okviru sastava geološke barijere, te je dominantna infiltracija procednih voda u podzemni tok. U skladu sa prvim slučajem, primenom softvera *STAN* realizovana je analiza tokova supstanci (SFA), primarno kadmijuma, u okviru tri scenarija. Efikasnost remedijacije zemljišta deponijskog lokaliteta kontaminiranog procednim vodama, sa aspekta redukcije teških metala, sa akcentom na kadmijum, primenom *in-situ* i *ex-situ* sistema, predstavljena je u okviru Scenarija 1 i Scenarija 2. Mogućnost i efikasnost direktnog tretmana procednih voda u postrojenju za tretman istih, u slučaju implementacije i primene sistema za upravljanje procednim vodama, predstavljena je u okviru Scenarija 3. Efikasnost redukcije toka kadmijuma ostvarena u okviru Scenarija 1 iznosi 99.04 %, u okviru Scenarija 2 iznosi 55 %, dok u okviru Scenarija 3 iznosi 99.2 %, respektivno. Prevencija kontaminacije deponijskog lokaliteta procednim vodama primenom sistema za upravljanje istim predstavlja optimalnu opciju i poželjnu praksu, dok u slučaju već postojeće kontaminacije deponijskog lokaliteta i neposredne okoline, primenom *in-situ* sistema remedijacije zemljišta deponijskog lokaliteta, na osnovu dobijenih rezultata, ostvaruje se visoka efikasnost, nasuprot primeni *ex-situ* sistema.