LIFE Environment and Resource Efficiency project

“Nutrient recycling circular economy model for large cities – water treatment sludge and ashes to biomass to bio-energy “

Project Acronym: NutriBiomass4LIFE
Project Number: LIFE17 ENV/LT/000310

Municipal waste-water treatment sludge recycling in NutriBiomass4LIFE circular economy model

WEB Report prepared by

UAB “Pageldynių plantacija”

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Preface

The purpose of this document is to provide insights on municipal waste-water treatment sludge recycling in biomass plantations action (B2) during implementation of the project NutriBiomass4LIFE. Over 4 years of implementation of the project total 16500 t of dried municipal waste-water treatment sludge digestate were recycled in NutriBiomass4LIFE biomass plantations, 795 t of total nitrogen (N), 361 of total phosphorus (P) and 55 t of total potassium (K) were recycled in 937 ha of biomass plantations, and that action had generated negative 22470 tCO2 footprint.

For the implementation of the NutriBiomass4LIFE project, a subsidy is awarded from the EU LIFE program, the EU's funding instrument for environment and climate action. The funding of the project also come from the Swedish Energy Agency and Ministry of Environment of the Republic of Lithuania.

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II. About the NutriBiomass4LIFE Project

The Nutribiomass4LIFE project was launched on 1 July 2018 and will be running until the end of September 2023. Within the framework of this project, 6 beneficiaries from Lithuania and Sweden aim to create and demonstrate the first of its kind on the EU level full scale self-sustainable closed loop circular economy model for large cities' nutrient rich waste - municipal wastewater treatment sludge and biomass ashes – recycling into renewable energy for city's needs via environment friendly biomass plantation phytoremediation filter. The circular economy model is based upon Vilnius city, the capital of Lithuania (550 thousand population).

The specific objectives of the project included:

- promoting resource efficiency through reuse of nutrients (less usage of mineral fertilizer) and decrease in transportation distances and flows;
- promoting waste management pyramid priorities via changing path from landfilling and incineration of nutrient rich waste towards reuse in biomass growth improvement;
- mitigation of food chain contamination risks via changing path of nutrient rich waste from uncontrolled usage in food crop growing towards 100% legally compliant and monitored non-food biomass yield improvement;
- creating new best practices for dried MWTS digestate usage for non-food biomass;
- developing new business models to make biomass growing / forestry on marginal and less suitable to agriculture soils economically attractive via substantial biomass yield improvement;
- promoting soil organic content improvement via bio-solids applications;
- promoting renewable energy production;
- promoting afforestation of less suitable for agriculture / marginal lands;
- contributing significantly to climate change impact reduction by sequestrating significant volume of CO2 in the whole circular economy model value chain, promoting renewable energy production, soil carbon content improvement;
- promoting of EU and national legislation and policies and contributing to their development by promoting safe and environment friendly reuse of nutrients from wastes.

The Coordinating beneficiary:

1. UAB "Pageldynių plantacija" (Lithuania)

Associated beneficiaries:

2. Forest and Landowners Association of Lithuania (Lithuania)
3. Lithuanian Research Centre for Agriculture and Forestry (Lithuania)
4. UAB "Kirtimu katiline" (Lithuania)
5. UAB "Vilniaus vandenys" (Lithuania)
6. Swedish University of Agricultural Sciences (Sweden)

For more information, please visit the project's website: www.nutribiomass.eu.

III. List of Abbreviations and Partner Acronyms

NutriBiomass4LIFE	EU LIFE project "Nutrient recycling circular economy model for large cities – water treatment sludge and ashes to biomass to bio-energy ", No. LIFE17 ENV/LT/000310
AGB	Above ground biomass
AV	UAB "Aukštaitijos vandenys", Panevėžys city municipal water supply and sewage water treatment company
AGROLAB	Lithuanian Research Centre for Agriculture and Forestry
BGB	Bellow ground biomass
CE	Circular economy
CO2	Carbon dioxide
Corg	Organic carbon
CRCF	Carbon Removal Certification Framework
dmt	Dry matter ton (t)
DMWTSD	Dried granulated municipal waste-water treatment sludge digestate
EU	European Union
FTE	Full time employed
g	gram, 1 kg = 1000 g
GHG	Greenhouse gases
kg	kilogram, 1 t = 1000 kg
ha	hectare, 1 ha = 1000 square meters
K	Potashium, total
KaunoV	UAB "Kauno vandenys", Kaunas city municipal water supply and sewage water treatment company
KedV	UAB "Kėdainių vandenys", Kėdainiai city municipal water supply and sewage water treatment company
km	kilometre, 1 km = 1000 m
LAND 20-2005	"Rules of waste-water treatment sludge usage in fertilization and land reclamation LAND 20-2005" issued by the Minister of environment of the Republic of Lithuania
LMSA	Forest and landowner's association of Lithuania
µ	microgram, 1 mg = 1,000 µg
mg	milligram, 1 g = 1000 mg
MWTS	municipal waste-water treatment sludge
N	Nitrogen, total
N_{min}	Mineral nitrogen
P	Phosphorus, total
PP	UAB "Pageldyniu plantacija"
PE	UAB "Kirtimu katiline", biomass boiler in Vilnius city
r. or reg.	administrative district
RED II	Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources
RED III	Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652
sen.	regional units of administrative district
SOC	Soil organic carbon
SSD	Directive 86/278/EEC of 12 June 1986 on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture (Sewage Sludge Directive)
t	metric ton, 1 t = 1000 kg
UWWTD	Urban Waste Water Treatment directive (91/271/EEC) and revision proposals adopted by council on October 16, 2023
VV	UAB "Vilniaus vandenys", Vilnius city municipal water supply and sewage water treatment company

Introduction

1.1 Purpose and Aim

The purpose of this document is to reveal the results of dried municipal waste-water treatment sludge digestate in biomass plantations (B2) during implementation of the project NutriBiomass4LIFE.

1.2 Structure

The document is divided into four main chapters:

- Chapter 1 “Role of MWTS in circular economy” defines rationale for using MWTS in circular economy.
- Chapter 2 “DMWTSD supply” discloses volume of MWTS supplied during NutriBiomass4LIFE project for recycling in biomass plantations.
- Chapter 3 “Quality of DMWTSD” discusses nutrient and contaminant content of DMWTSD used during NutriBiomass4LIFE project for recycling in biomass plantations.
- Chapter 4 “DMWTSD recycling technology” discusses DMWTSD recycling in biomass plantations technology employed during NutriBiomass4LIFE project.
- Chapter 5 “DMWTSD recycling locations” discloses land plots in which DMWTSD was used for recycling in biomass plantations during NutriBiomass4LIFE project.
- Chapter 6 “Nutrient recycling” discloses volumes of nutrients recycled from DMWTSD in biomass plantations during NutriBiomass4LIFE project.
- Chapter 7 “Heavy metal inputs” discloses volumes of heavy metals recycled from DMWTSD in biomass plantations during NutriBiomass4LIFE project and associated risks.
- Chapter 8 “Economics of DMWTSD recycling” discloses costs of DMWTSD recycling in biomass plantations and potential revenues for yield increases.
- Chapter 9 “Carbon footprint” discloses CO2 footprint of DMWTSD recycling in biomass plantations during NutriBiomass4LIFE project.
- Chapter 10 “Policy” discusses policy and national legislation issues related to DMWTSD recycling.
- Chapter 11 “Continuation” discusses DMWTSD recycling in biomass plantations replication and transfer plans.
- Chapter 12 “Conclusions” provides key finding from DMWTSD recycling in biomass plantations action of Nutribiomass4LIFE project.

1 Role of MWTS in circular economy

Sewage sludge is a nutrient rich waste which results from the waste water treatment process and is a sink of both nutrients and contaminants.

EU policies, e.g. Urban Waste Water Treatment directive, have strong been focuss on high standards in waste water treatment. Recently, with implementation of Circular economy policies, management and reusage of sewage sludge as soil biosolids, or the recovery from it of valuable energy and key nutrients (such and Nitrogen (N) and Phosphorus (P)) starts to get more attention. The recovery and reusage of key nutrients are of great interest as EU moves towards a more circular economy under the Green Deal, also pursuing a zero-pollution targets.

The most important elements, important for sewage sludge usage in agriculture and forestry are as follows:

- Nitrogen (N) – 4-6%
- Phosphorus (P) – appr. 1,5-3 %
- Organic carbon – 20-60%
- Calcium – appr. 6%

Besides key macronutrient and organic carbon, which is very important for soil health improvement to restore humus content, sewage sludge is abundant with all micro-nutrients, which content differs upon inflowing waste-water inputs.

Sewage sludge is also a valuable energy source as it contains significant amount of carbon. When sewage sludge is landfilled, sludge becomes a source of significant CO2 emissions, when it is used in agriculture or biomass plantations it becomes significant source of carbon sink. Modern sewage sludge processing through anaerobic digestion allows to recover carbon in the form of biogas, which can be converted into renewable transportation fuels or used for heat and power production. Another popular pathway for energy recovery from sewage sludge is incineration, but co-incineration without nutrient recovery at waste incineration plants or cement production plants leads to losing all valuable nutrient pools therefore is considered only one step better than landfilling in the hierarchy of waste management.

Sewage sludge is not only resources but also hazard. Although during recent decades, much stricter requirements for upstream discharge water substantially reduced heavy metal content in sewage sludge and modern sludge management practices allow to avoid risks related to parasites, still heavy metal concentrations may pose certain risks for the environment and human health. The key heavy metals in sewage sludge, concentrations of which are limited by EU Sewage Sludge directive (SSD) and national regulation while using in agriculture are Cuprum (Cu), Lead (Pb), Zink (Zn), Nickel (Ni), Chrome (Cr), Cadmium (Cd) and Mercury (Hg).

Over recent years, the other dangerous substances like organic contaminants, pharmaceuticals, and microplastics emerged and there is a growing concern that these substances can be proliferated in the environment and can have long term negative impact on the environment and human health.

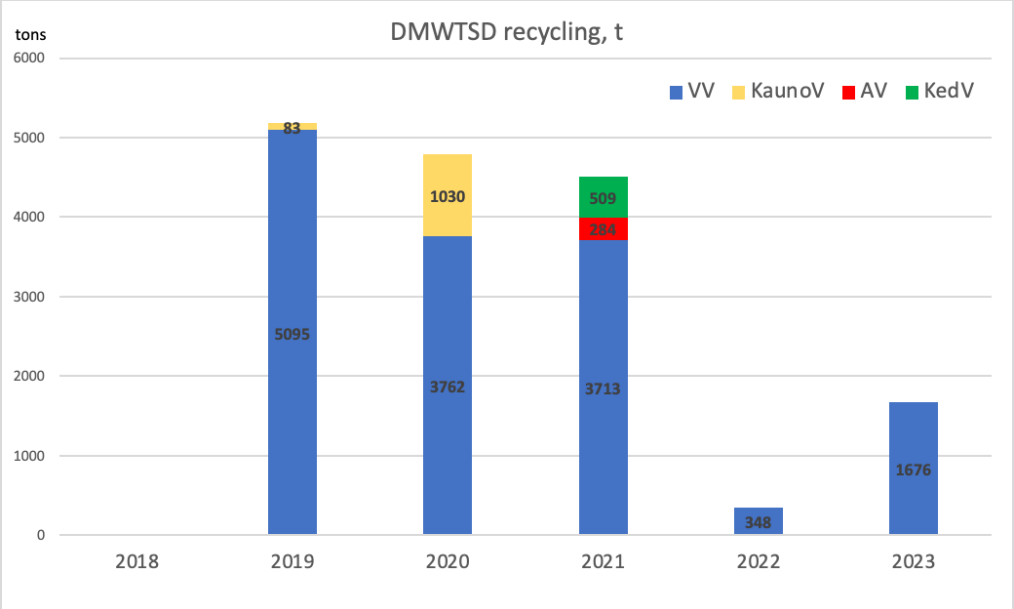
Public concern about human health risks due to contamination is driving a shift away from agricultural uses, towards search of alternative sewage sludge management approaches that ensure nutrient recovery while controlling contaminants, such as P recovery from incineration ash. But during mono-incineration with the target to recover phosphorus, all other nutrient pools, including valuable nitrogen and organic carbon are lost or used. Therefore, a sewage sludge management pathway to use it in fertilization of non-food crops, like biomass, allows to avoid risks of contamination of food chain and human health.

2 DMWTSD supply

In 2018, via international open tender, VV procured services for dried waste-water treatment sludge digestate recycling in biomass plantations and signed contract to provide up to 27,000 dmt of DMWTSD for recycling in biomass plantations. The contractor transported DMWTSD, packed in big bags (during off fertilization season) or unpacked, from VV waste-treatment plant directly to the field and used it for fertilization of established biomass plantations.

During implementation of the Nutribiomass4LIFE project (action B2) total 16500 dmt of DMWTSD was supplied and recycled in NutriBiomass4LIFE biomass plantations. 14894 dmt of DMWTSD was supplied by VV (88%), 1133 dmt by KaunoV (6,8%), 509 dmt by KedV (3,1%) and 284 dmt by AV (1,7%).

Picture 2-1. Annual DMWTSD recycling in NutriBiomass4LIFE biomass plantations, t



National legislation defines that MWTS cannot be recycled on land from mid of November till beginning of April, therefore during this period MWTS has to be stored.

According to the project plan VV had to supply 27000 dmt (or 9000 dmt / year) of DMWTSD. Technical problems of the digestate drying process and unexpected decrease in the overall DMWTSD production by more than 10% (since 2020 actual annual output of VV of DMWTSD was bellow 9000 dmt) were the major obstacles to ensure sufficient supply of DMWTSD from VV at the beginning of the project. Only 56,6% of targeted recycling output was achieved in 2019.

In late autumn of 2019, DMWTSD drying line of VV undergone major repair to achieve targeted output of dried DMWTSD in 2020. Unfortunately, the repair could not ensure stable operations of DMWTSD drying line. Additionally, COVID-19 had major impact on disruption of supplies in DMWTSD from VV in 2020, as VV could not ensure timely supplies of spare parts for drying line due to stopped operations at equipment supplier plants in the EU for COVID-19 reasons. At the end of August 2020 VV stopped production of DMWTSD as spare part supplies were not available due to COVID-19 impact and resumed its operations only end of that year. Therefore, in 2020 VV supplied only 3762 dmt of DMWTSD.

Unsolved technical problems did not allow VV to increase DMWTSD recycling in NutriBiomass4LIFE project in 2021 as well, as only 3713 dmt of DMWTSD were supplied for recycling in NutriBiomass4LIFE plantations.

Since VV was not able to ensure sufficient ant stable supplies of targeted quantity of DMWTSD, PP tried to compensate missing quantities form other major municipal waste—water treatment plants of Lithuania, as it was defined in risk management plan of NutriBiomass4LIFE project application.

Already in 2020, first 83 dmt of DMWTSD from UAB “Kauno vandenys” (KaunoV), the second largest city in Lithuania were recycled in NutriBiomass4LIFE biomass plantations. In 2020, DMWTSD supply from KaunoV for recycling in NutriBiomass4LIFE plantations increased to 1030 dmt. Additionally, in 2021 for recycling in NutriBiomass4LIFE plantations 284 dmt of DMWTSD were supplied by AV (“Aukštaitijos vandenys“ - municipal waste water treatment plant of Panevėžys, fifth largest city in Lithuania) and 509 dmt of DMWTSD were supplied by KedV (“Aukštaitijos vandenys“ - municipal waste water treatment plant of Panevėžys.)

From 2020 PP expected to compensate shortage of DMWTSD of VV by recycling DMWTSD supplied from other waste-water treatment plants, mainly from Kaunas and Panevėžys cities. Unfortunately, in 2020 new waste incineration facilities started to operate in Kaunas city and Akmene cement plant (Akmene city) which were looking for solid waste supply for incineration. As MWTS according to EU regulation is considered a renewable resource, Akmene cement plant can benefit from received free Emission Allowances by incinerating MWTS by replacing coal burning. This makes incineration of DMWTSD much more competitive than using in Circular Economy model (recycling and reusage in agriculture and biomass plantations).

From January 1, 2021 the newly introduced legislation in Lithuania related to WMTS recycling in agriculture and biomass plantations projected a clear shift towards circular economy: it stated the WMTS could be incinerated or used for landfill coverage only in case fertilization option would not be available. Unfortunately, this new legislation was very quickly changed by the new government under the lobby of waste incineration plants and cement production plant, making no priority for usage of WMTS in circular way over incineration.

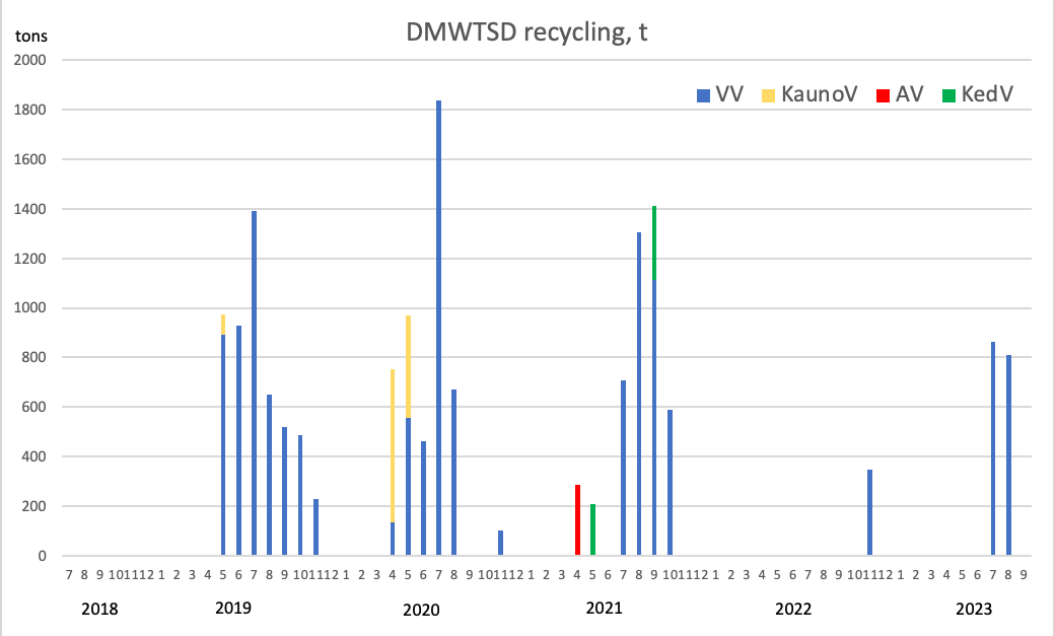
In 2022 the war in Ukraine and it’s triggered global energy crisis, particularly in the EU, had much severe impact on NutriBiomass4LIFE project activity related to DMWTSD recycling in biomass plantations. In 2022 as a part of EU energy crisis solution to reduce natural gas consumption MWTS drying facilities of all Lithuanian waste-water treatment plants temporary stopped their operations. As VV still continued to produce some DMWTSD using biogas, to combat energy crisis in 2022 VV primary

supplied DMWTSD to Akmene cement plant for incineration to replace coal. Therefore, in 2022 VV supplied only 348 dmt of DMWTSD for recycling in NutriBiomass4LIFE project.

In 2023 after energy crises and energy prices for natural gas subsided, VV renewed drying operations of MWTS and recycling of DMWTSD in NutriBiomass4LIFE project. In 2023, 1676 dmt of DMWTSD were recycled at NutriBiomass4LIFE biomass plantations.

All these above listed developments in DMWTSD supply during NutriBiomass4LIFE project implementation can be observed in Picture 2-2, where monthly DMWTSD quantities recycled in NutriBiomass4LIFE project are presented.

Picture 2-2. Monthly DMWTSD recycling in NutriBiomass4LIFE biomass plantations, t



Nutrient recycling form large cities is a significant and complicated logistic operation. Total 1091 large trucks were engaged to transport DMWTSD from municipal waste-water treatment plants to NutriBiomass4LIFE plantations for recycling.

Table 2-1. DMWTSD supply to NutriBiomass4LIFE project

DMWTSD supplier	Number of trucks	DMWTSD supplied, t
VV	992	14594
KaunoV	47	1113
AV	30	284
KedV	22	509
TOTAL	**1091**	**16500**

3 Quality of DMWTSD

DMWTSD quality is characterised by positive impact from nutrients and other soil improvement elements and by negative impacts which comes from potential contaminants.

Positive impact from reusage of DMWTSD in soil is coming mainly from Nitrogen (N), Phosphorus (P), Calcium (Ca), Potassium (K), organic carbon (Corg) and various micronutrients. Negative impact on usage of DMWTSD on soil is coming from heavy metals, PAH, PCB, microplastics, etc.

3.1 Nutrient content

MWTS is as fertilizer is primary valued due to two abundant macronutrient content: Nitrogen (N) and Phosphorus (P). The key mean macro and micro-nutrient concentrations in reused DMWTSD are presented in the Table 3-1.

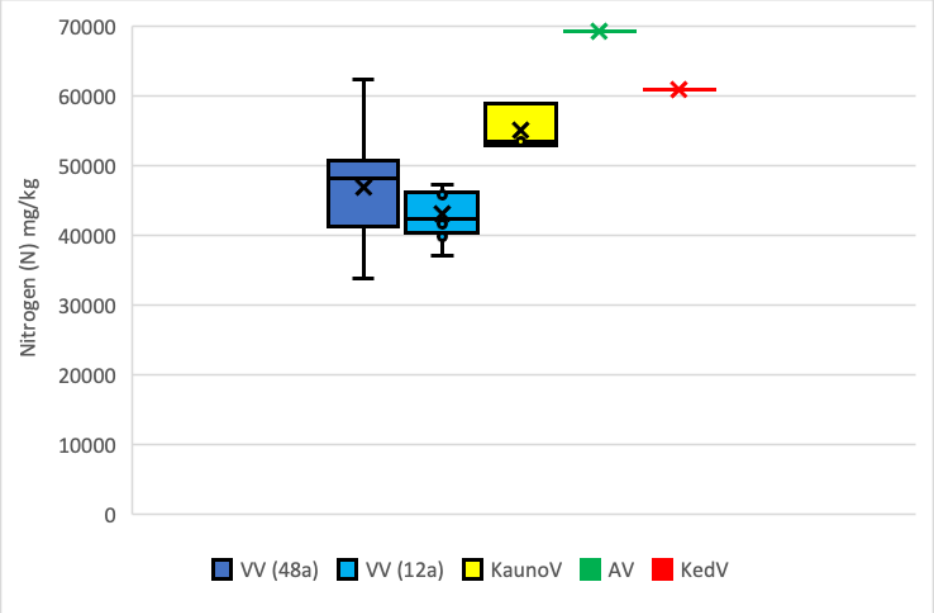
Table 3-1. Mean values of nutrient content in DMWTSD

Nutirent values	units	VV (48 samples)	VV (12 samples)	KaunoV (3 samples)	AV	KedV
pH		6,7	7,3	7,4	6,3	6,8
Total organic matter	%	55,4	58,4	65,3	66,9	39,3
Total nitrogen (N)	mg/kg	46911	43122	55169	69408	60900
Total phosphorus (P)	mg/kg	22290	27375	29363	22659	24800
Potassium (K)	mg/kg		3267	4600	4500	1890
Calcium (Ca)	mg/kg		60000			
Magnesium (Mg)	mg/kg		11267			
Manganese (Mn)	mg/kg		295			
Ammonia nitrogen (N-NH4)	mg/kg		1427			
Nitrate nitrogen (N-NO3)	mg/kg		270			
Total sulphur (S)	mg/kg		7332	6200		
Total organic carbon (Corg)	%		22,2	36,32		

The key macronutrient in DMWTSD, which is very important for biomass yield improvement on low fertility soils is Nitrogen (N). Mean total Nitrogen (N) concentrations in DMWTSD were 46911 mg/kg in 48 samples of VV and 43122 mg/kg in 12 samples of VV. Mean total Nitrogen (N) concentrations in DMWTSD of VV was 20-30% lower comparing to other municipal waste-water treatment plants – KaunoV (55169 mg/kg), KedV (60900 mg/kg) and AV (69408 mg/kg).

Most nitrogen in DMWTSD is in organic form. Analysis reveals (VV 12 samples) that Ammonia nitrogen (N-NH4) is only 3,3% and Nitrate nitrogen (N-NO3) is only 0,6% in total nitrogen (N) of DMWTSD. Organic nitrogen is slowly released and becomes plant available over several years and it allows to plan to use DMWTSD as fertilizer once in several years by adding higher rates of organic Nitrogen (N) without increasing risk of leaching of mineral nitrogen in ground and surface waters. This type of nutrient rich waste in particular is suitable for biomass plantation fertilization, which allows to decrease negative impact on soil and soil organic carbon while inserting DMWTSD and to decrease leaching risks.

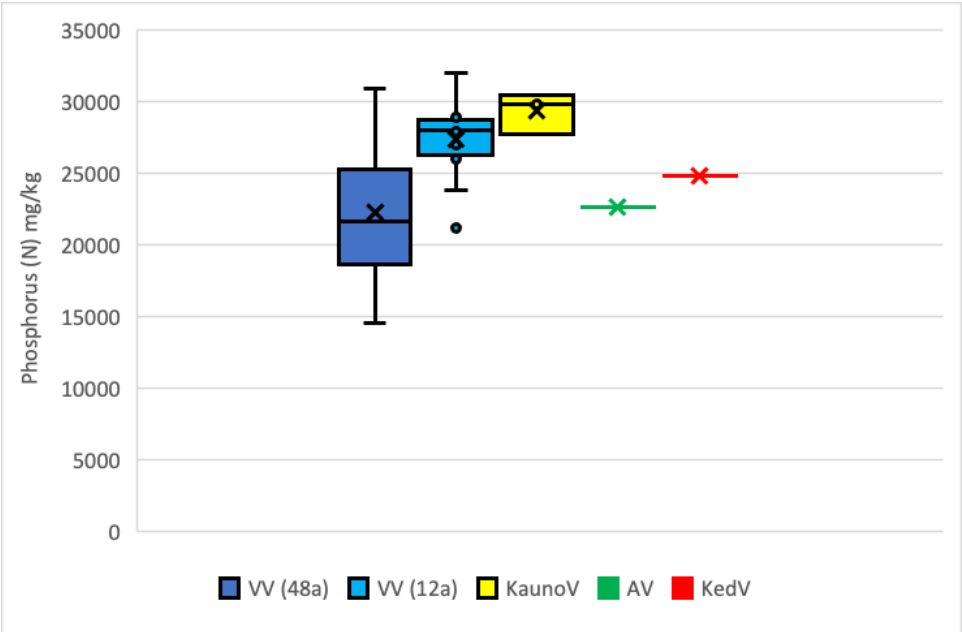
Picture 3-1. Total Nitrogen (N) concentrations in DMWTSD, mg/kg



DMWTSD is one of the types of nutrient rich wastes, which has high phosphorus (P) concentrations. Therefore, DMWTSD is viewed as very important alternative source of phosphorus (P) to phosphorus rock, which is a finite resource.

Analysis shows that mean phosphorus (P) concentrations in DMWTSD were 22290 mg/kg in 48 samples of VV and 27375 mg/kg in 12 samples of VV. Mean total Phosphorus (P) concentrations in DMWTSD of VV are similar to other municipal waste-water treatment plants – KaunoV (29363 mg/kg), KedV (24800 mg/kg) and AV (22659 mg/kg). The new Urban Waste Water Treatment directive, adopted in October 2023, imposes more strict water treatment regulation regarding phosphorus and nitrogen and will result in higher concentrations of phosphorus and nitrogen in MWTS.

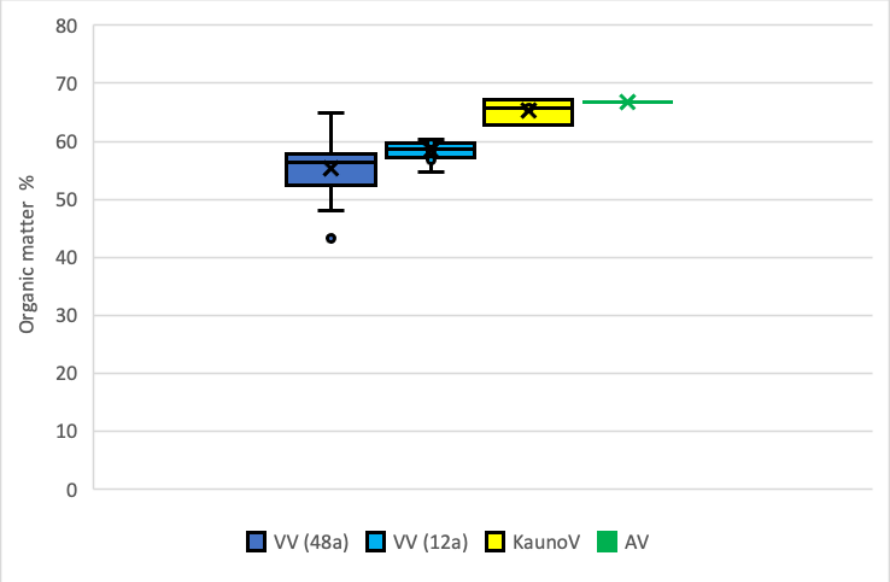
Picture 3-2. Total Phosphorus (P) concentrations in DMWTSD, mg/kg



One more important aspect of DMWTSD, which has strong positive impact over soil quality improvement and biomass yield growth is organic matter (%) and in particular organic carbon (%) content.

Analysis shows that mean organic matter content in DMWTSD were 55,4 % in 48 samples of VV and 58,4 % in 12 samples of VV, 65,3 % of KaunoV, and 66,9% of AV. Organic carbon in DMWTSD of VV was 22,2% and of KaunoV was 36,3%.

Picture 3-3. Total organic matter content in DMWTSD, %



Total organic matter content in DMWTSD of VV is lower comparing to other municipal waste-water treatment plants of Lithuania, as VV has more advanced sludge processing technology which uses thermal hydrolysis and due to which production of biogas through anaerobic digestion is substantially higher at VV MWTS processing facility, which uses more carbon from MWTS in biogas production. This can be observed if comparing organic carbon content in DMWTSD: organic carbon content (22,2%) in DMWTSD of VV is more than 50% lower comparing to DMWTSD of KaunoV (36,3%).

3.2 Contaminants

Despite abundant nutrients, application of DMWTSD in agriculture/forestry contains certain risks related to heavy metal, organic contaminant, microplastics, etc.

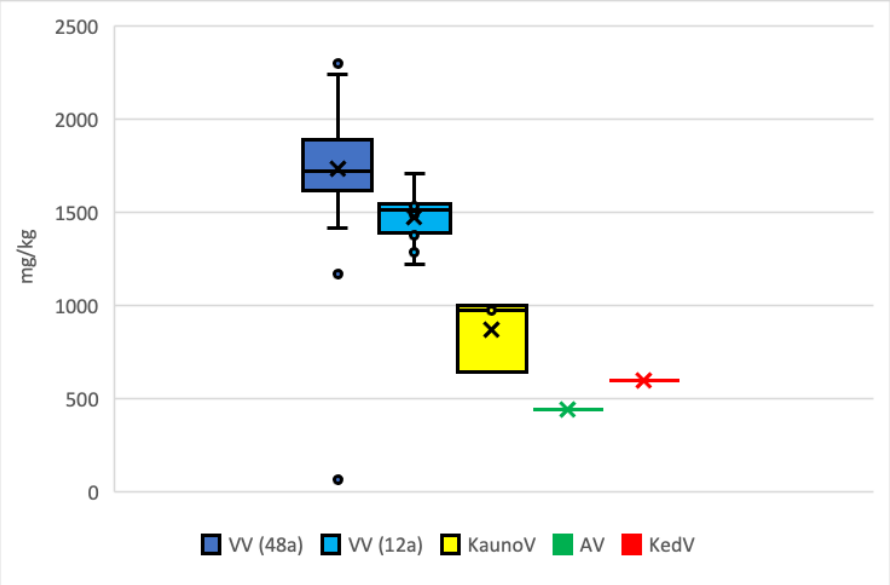
Heavy metal concentration limits in MWTS are regulated by EU (EU Sludge directive 86/278/EEC) and national sludge directive (LAND 20-2001). National sludge directive sets much stricter heavy metal concentration comparing to EU Sludge directive 86/278/EEC. Overall sludge contamination in MWTS was significantly decreasing over years – as polluting heavy industries either closed their operations, either switched to much cleaner technologies and installed local water cleaning facilities. Nevertheless, Vilnius city has the most contaminated water inflows form population and industries, and heavy metal concentrations in MWTS remain the highest in Lithuania.

Table 3-2. Mean concentrations of heavy metals in DMWTSD

Contaminant concentrations	units	Limiting concentrations in DMWTSD for usage in biomass plantations		VV (48 samples)	VV (12 samples)	KaunoV (3 samples)	AV	KedV
		EU sludge directive	National					
Cuprum (Cu)	mg/kg	1000-1750	1000	305	286	202	83	180
Lead (Pb)	mg/kg	750-1200	150	44	43	35	27	6
Zink (Zn)	mg/kg	2500-4000	2500	1707	1476	874	444	600
Nickel (Ni)	mg/kg	300-400	70	50	54	34	14	23
Chrome (Cr)	mg/kg		170	68	54	65	17	65
Cadmium (Cd)	mg/kg	20-40	5	1,8	2,7	2,7	0,9	0,8
Mercury (Hg)	mg/kg	16-25	1,5	0,59	0,02	0,02	0,02	0,47

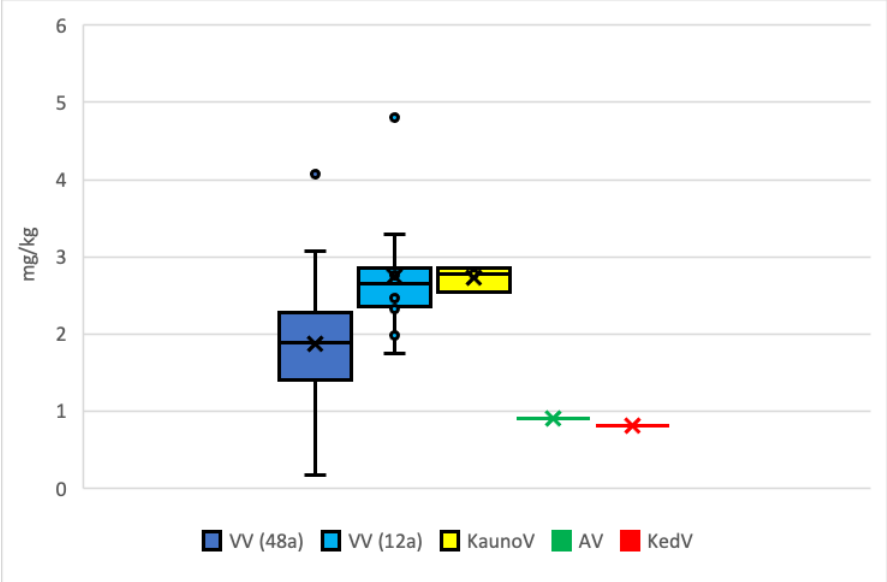
In terms of heavy metal concentrations, the highest risk in DMWTSD of VV is related to Zink (Zn), which is also considered as micro-nutrient. Mean Zink (Zn) concentrations in DMWTSD were 1707 mg/kg in 48 samples of VV and 1476 mg/kg in 12 samples of VV and was 2 times higher than in other municipal waste-water treatment plants – KaunoV (874 mg/kg), AN (444 mg/kg) and KedV (600 mg/kg).

Picture 3-4. Concentrations of Zink (Zn) in DMWTSD, mg/kg



Cadmium is one of the most dangerous heavy metals for human health, therefore its concentrations are strictly regulated. Over the years cadmium concentrations in MWTS of Lithuanian municipal waste-water treatment plants decreased substantially. Mean Cadmium (Cd) concentrations in DMWTSD were 1,8 mg/kg in 48 samples of VV, 2,7 mg/kg in 12 samples of VV, 2,7 mg/kg in KaunoV, 0,9 mg/kg in AN and 0,88 mg/kg in KedV.

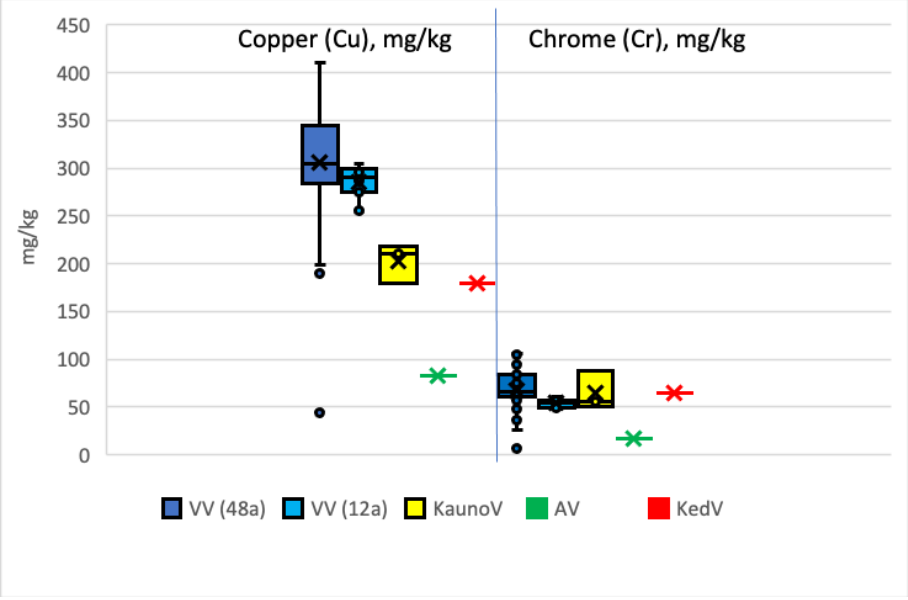
Picture 3-5. Concentrations of Cadmium (Cd) in DMWTSD, mg/kg



Mean Cuprum (Cu) concentrations in DMWTSD were 305 mg/kg in 48 samples of VV and 286 mg/kg in 12 samples of VV and was more than 1,5 times higher comparing to other municipal waste-water treatment plants – KaunoV (202 mg/kg), AV (83 mg/kg) and KedV (180 mg/kg), but still was 3,3 times lower than highest concentration allowed in MWTS according national legislation.

Mean Chrome (Cr) concentrations in DMWTSD were 68 mg/kg in 48 samples of VV and 54 mg/kg in 12 samples of VV and was similar in other municipal waste-water treatment plants – KaunoV (65 mg/kg), KedV (65 mg/kg), but still was 2,5-3 times lower than highest concentration allowed in MWTS according national legislation.

Picture 3-6. Concentrations of Cuprum (Cu) and Chrome (Cr) in DMWTSD, mg/kg

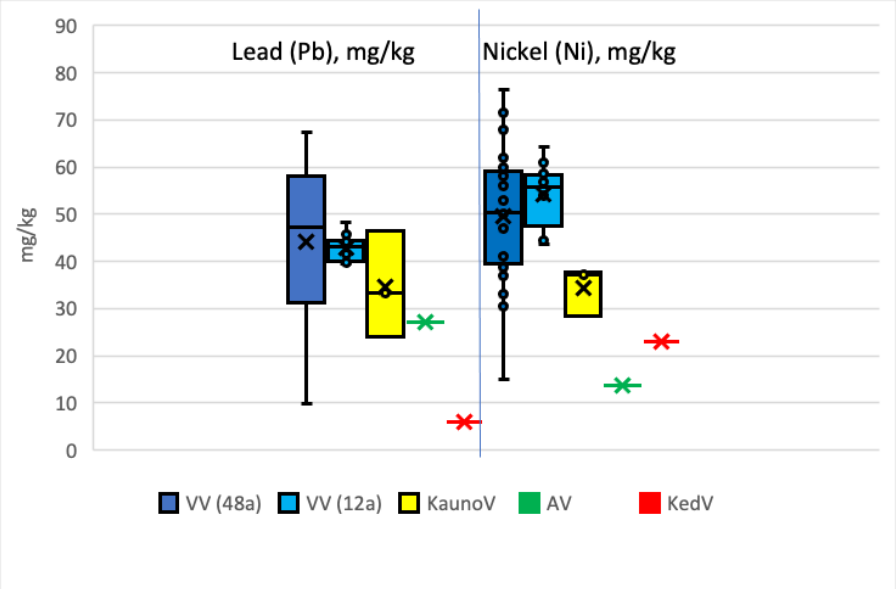


Mean Lead (Pb) concentrations in DMWTSD were 44 mg/kg in 48 samples of VV and 43 mg/kg in 12 samples of VV and was higher comparing to other municipal waste-water treatment plants – KaunoV

(35 mg/kg), KedV (27 mg/kg) and AV (6 mg/kg), but still was 3,5 times lower than highest concentration allowed in MWTS according national legislation.

Mean Nickel (Ni) concentrations in DMWTSD were 50 mg/kg in 48 samples of VV and 54 mg/kg in 12 samples of VV and was more 1,5-2 times higher comparing to other municipal waste-water treatment plants – KaunoV (34 mg/kg), KedV (23 mg/kg) and AV (65 mg/kg).

Picture 3-7. Concentrations of Lead (Pb) and Nickel (Ni) in DMWTSD, mg/kg



In general concentrations of heavy metals in MWTS in Lithuania should not be considered risky, and in mane cases (with exception of large cities), MWTS meets heavy metal concentration requirements for fertilizing product regulation.

4 DMWTSD recycling technology

Dried granulated municipal waste-water treatment sludge (DMWTSD) is suitable form of MWTS for fertilization in biomass plantations – it is easy to store, transport and spread in the fields with growing trees and ammonia concentrations are low preventing form nitrogen leakage.

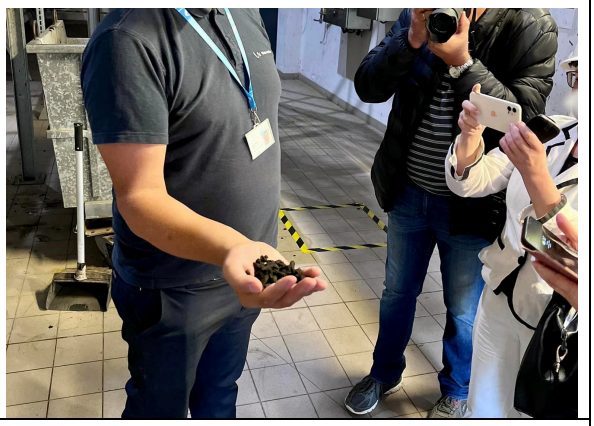
In VV, DMWTSD after drying are stored in two silos, from which DMWTSD are either packed into big-bags (each of 1,5 cub. m and up to 650-750 kg) or supplied for fertilization unpacked. Packed in bags DMWTSD is transported to the fertilized fields by conventional trailers, loading 22 bags in each trailer – netto weight of one trailer is about 14,6 t.

DMWTSD also can be supplied unpacked, filling special trailers with DMWTSD directly from storage silos. In this case net wight depends on type of special trailer used – trailers used for transportation of energy chips can transport up to 24 t/trailer of DMWTSD, trailers used for transportation on bulk construction material or waste can transport from 16 to 20 t/trailer.

After transporting to biomass plantations, DMWTSD is loaded into compost spreaders and is spread among established trees. After spreading, with the help of disking DMWTSD is inserted into soil.

Picture 4-1. DMWTSD production, storage and transportation







Picture 4-2. DMWTSD recycling in biomass plantations










5 DMWTSD recycling locations

During the project DMWTSD as biomass plantation fertilizing and soil amendment material was used in multiple locations with established woody-biomass crops (hybrid poplar, hybrid aspen and willows) and total 937 ha area was fertilized. In most cases biomass plantations were fertilized with DMWTSD exclusively, while 147 ha in Anykščai district were fertilized with combined DMWTSD and biomass ashes.

In the table 5-1 all locations (land plots) are presented, providing information on annual recycling of DMWTSD and average fertilization rates used. Fertilization rates using DMWTSD varied over project time with changes in national legislation (LAND 20-2001). Till 2021 it was allowed to use up to 33 dmt/ha of DMWTSD fertilization rate once in three years for fertilization purposes in biomass plantations and limiting factor was heavy metal zinc (Zn) concentrations in DMWTSD. Since 2021 fertilization rate of DMWTSD in biomass plantations was reduced till 11 dmt/ha once in three years for new environmental permits, but valid environmental permits can still use previous fertilization rates. Therefore, biomass plantation fertilization rates during NutriBiomass4LIFE project implementation varied from 11 dmt/ha to 33 dmt/ha and averaged 17,61 dmt/ha of DMWTSD.

Table 5-1. Locations and DMWTSD used for soil amendment and fertilization

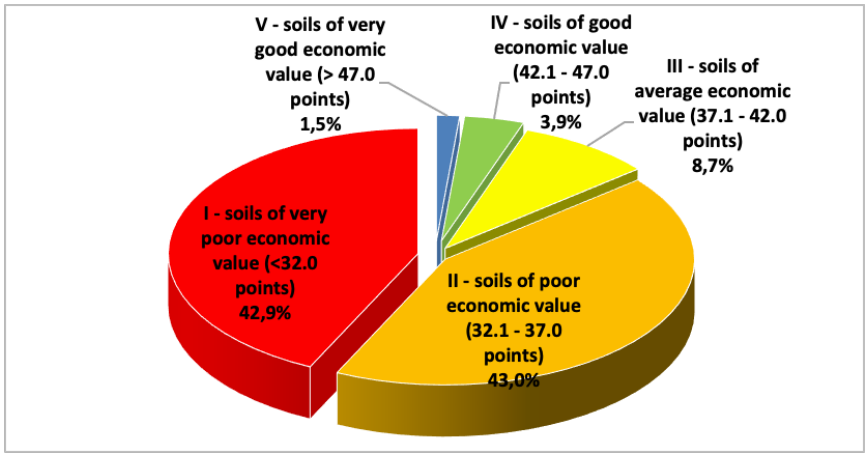
Address	Land plot Unique No.	Fertiliza-tion area, ha	Av. ferti-lization rate dmt/ha	2019 dmt	2020 dmt	2021 dmt	2022 dmt	2023 dmt	Total dmt
TOTAL		**936,9**	**17,61**	**5178**	**4792**	**4506**	**348**	**1676**	**16500**

6 Nutrient recycling

According to soil analysis, performed by AGROLAB, absolute majority of biomass plantations included in NutriBiomass4LIFE model are established on poor quality soils, which are not suitable for efficient intensive agriculture.

When classifying the soils of the project fields by productivity score, AGROLAB used the nationally determined land productivity scores of agricultural land soils in each cadastral area of the country, which are extracted according to the LTDK-99 classification in the contours of soil types. These scores are publicly available to every resident of the country on the portal www.zis.lt. where they are periodically renewed based on soil analysis through national soil monitoring program. Comparing to historic information extracted from the State register centre, productivity score of soils has a clear tendency of decreasing, especially in areas with natural constraints. The fields of NutriBiomass4LIFE biomass plantations are located in the Eastern part of the country, in Vilnius, Švenčionys, Širvintos, Molėtai, Anykščiai and Trakai districts, where the poorer and infertile soils prevail. Picture 6-1 shows the distribution of the NutriBiomass4LIFE biomass plantation soils according to their assignment to the corresponding soil productivity score - we can see that the soils of the majority of the fields are of poor (32.1-37.0 points) and very poor (<32.0 points) economic value and these poor soils make up 85.9% in total.

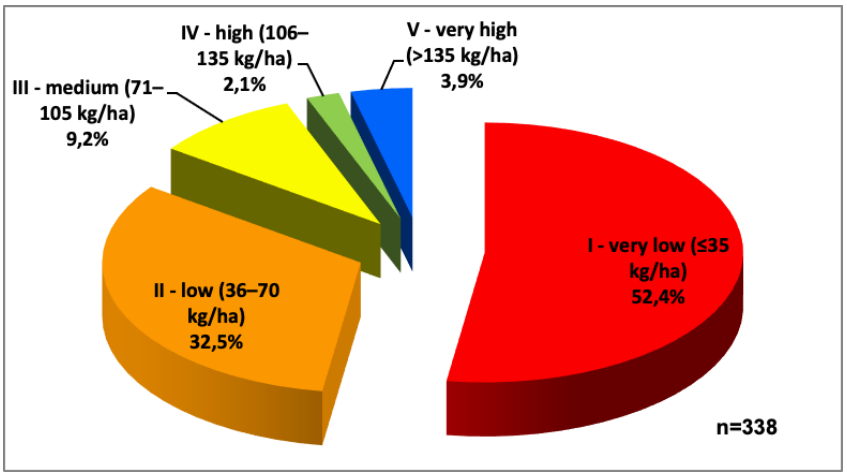
Picture 6-1. Distribution of NutriBiomass4LIFE plantation soils according productivity score



Low productivity sore is in major determined by low mineral nitrogen and phosphorus content in such soils. The amount of mineral nitrogen (N_{min}) in the soil changes noticeably during the year depending on the fertilization of plants with organic and mineral fertilizers, climatic conditions, applied tillage, the type of cultivated plants, the genesis of the soil and its texture composition, and the nitrogen content in the soil. Soils with a heavier texture composition, containing more clay and dust particles, accumulate more mineral nitrogen than light ones, from which nitrogen migration occurs more intensively. Although nitrogen is one of the essential factors shaping soil and plant fertility, its excess can be harmful to the environment.

The soils of Nutribiomass4LIFE plantations are located in the districts of Vilnius, Švenčionys, Širvintos, Molėtai, Anykščiai and Trakai and belong to the Eastern Lithuania zone, where soils with a lighter soil texture predominate, so this partly led to much lower concentrations of N_{min} in them, compared to the mineral soils prevailing in the relief of the plains of Central Lithuania. The distribution (%) of mineral nitrogen (N_{min}) in the 0-60 cm layer according to richness groups in the mineral soils of NutriBiomass4LIFE is presented in Picture 6-2. In total NutriBiomass4LIFE mineral soils (Picture 6-2), soils with very low (≤35 kg ha-1) and low (36-70 kg ha-1) N_{min} prevailed, making 83% of total soils.

Picture 6-2. Distribution of NutriBiomass4LIFE plantation mineral soils according N_{min} content



Plant available phosphorus (P_2O_5). Phosphorus, unlike some forms of nitrogen, is relatively stable in the soil and does not change easily. Due to its high stability and low solubility in soil, phosphorus is often considered as a missing element. In the soil, it is included in the composition of mineral and organic compounds. The initial distribution (%) of plant available phosphorus (P_2O_5) in the upper 0-20 cm layer according to richness groups in the mineral NutriBiomass4LIFE soils is presented in Picture 6-3. Initial mineral (Picture 6-3) soils of NutriBiomass4LIFE plantations were dominated by very low (≤50 mg kg-1) and low (51 -100 mg kg-1) soils containing mobile P2O5, making 72,4% of total soils in project.

Picture 6-3. Distribution of NutriBiomass4LIFE plantation mineral soils according P_2O_5 content

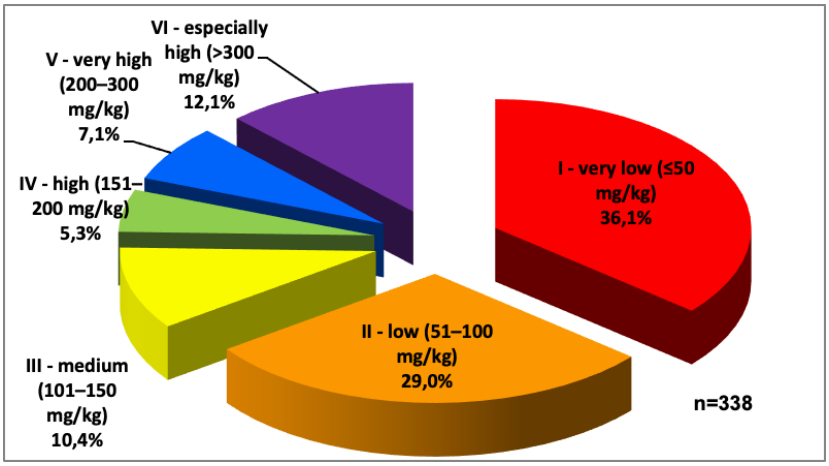


Table 6-1 provides detailed information on nutrients recycled after reusing of 16500 tons of DMWTSD in biomass plantations by specific land plots. Among nutrients, the largest volumes were reused of total nitrogen (N) – 795 t, total phosphorus (P) - 361 t, total potassium (K) – 54,7 t, total calcium (Ca) – 999 t, magnesium (Mg) – 186 t and total sulphur (S) – 120 t., which were added to NutriBiomass4LIFE soils.

Table 6-1. Total nutrient recycling volumes from DMWTSD, t

Address	Land plot Unique No.	Org. matter, t	N, t	P, t	K, t	Ca, t	Mg, t	S, t
TOTAL		9200	794,8	361,3	54,7	990,0	185,9	120,3

Table 6-2. Nutrient recycling volumes from DMWTSD, t, kg/ha/year (5 year project period)

Address	Land plot Unique No.	Org. matter, kg/ha/year	N, kg/ ha/year	P, kg/ ha/year	K, kg/ ha/year	Ca, kg/ ha/year	Mg, kg/ ha/year	S, kg/ ha/year
TOTAL		1964	170	77	12	211	40	26

Based on Table 6-2 data, significant volumes of nutrients were supplied to NutriBiomass4LIFE biomass plantation soils through recycling DMWTSD. This is important considering poor fertility of NutriBiomass4LIFE soils – significant lack of mineral nitrogen and plant available phosphorus.

On average 170 kg/ha/year (on 5 year basis) of total nitrogen (N) were added from recycling of DMWTSD to fertilized soils of NutriBiomass4LIFE plantations. Initially the volume of total nitrogen added to the soil was higher, when up to 33 dmt/ha of DMWTSD rate could be used. From 2021 total nitrogen input decreased to 82-90 kg/ha/year due to decreased to 11 dmt/ha DMWTSD fertilization rate in biomass plantations.

As mineral nitrogen is only about 4% in total nitrogen content of DMWTSD, it allows reduce the risk of nitrogen leakage significantly. At the same time, slow mineralization of organic nitrogen allows mineral nitrogen available for biomass plantation biomass yield increase over several years following fertilization with DMWTSD.

Similar situation can be observed with phosphorus inputs from DMWTSD application in NutroBiomass4LIFE biomass plantations.

On average 77 kg/ha/year (on 5 year basis) of total phosphorus (P) were added from recycling of DMWTSD to fertilized soils of NutriBiomass4LIFE plantations. Initially the volume of total phosphorus added to the soil was higher, when up to 33 dmt/ha of DMWTSD rate could be used. From 2021 total phosphorus (P) input decreased to 41-54 kg/ha/year due to decreased to 11 dmt/ha DMWTSD application rate in biomass plantations.

7 Heavy metal inputs

While reusing DMWTSD in NutriBiomass4LIFE plantations, the total highest amounts of heavy metal inputs included zinc (Zn) – 27,48 t and copper (Cu) – 4,87 t kg (Table 7-1). Above mentioned heavy metals are also considered as micronutrients, therefore they do not impose high risk to plants but have positive impact unless supplied at excessive concentrations.

From the point of heavy metal inputs DMWTSD into the soil as per mg/kg, the amount added to the soil is insignificant per all heavy metals analysed with exception of above-mentioned zinc (Zn) and copper (Cu). Share of total zinc (Zn) input in the highest allowed zinc (Zn) concentration in soil reached 6,32%, for copper (Cu) – 3,5%.

Share of total input of other heavy metals in the highest allowed heavy metal concentration in soil did not exceed 1,2% in all heavy metal cases and was highest in cadmium (Cd) - 1,16%, chromium (Cr) – 0,8%, mercury (Ni) – 0,63%, nickel (Ni) – 0,61% and lead (Pb) - 0,55%.

In addition, part of added heavy metals is being again absorbed by fast-growing trees into biomass, therefore no significant increase in heavy metal concentrations in soil is observed during DMWTSD application during NutriBiomass4LIFE project implementation.

Table 7-1. Total heavy metal inputs from DMWTSD

Address	Land plot Unique No.	Cu kg	Pb kg	Zn kg	Ni kg	Cr kg	Cd kg	Hg kg
TOTAL		**4869**	**743,6**	**27479**	**826,0**	**1090,9**	**31,4**	**8,54**

Table 7-2. Heavy metal inputs from DMWTSD, mg/kg soil

Address	Land plot Unique No.	Cu kg	Pb kg	Zn kg	Ni kg	Cr kg	Cd kg	Hg kg
TOTAL		**1,79**	**0,27**	**10,11**	**0,30**	**0,40**	**0,012**	**0,003**
Concentration limits in soil, mg/kg		**50**	**50**	**160**	**50**	**50**	**1**	**0,5**
Total input / concentration limits in soil		**3,58%**	**0,55%**	**6,32%**	**0,61%**	**0,80%**	**1,16%**	**0,63%**

Note: Average density of top 0-20 layer of soil: sandy loam (1,40 g/cm3) and organic (0,80 g/cm3)

8 Economics of DMWTSD recycling

The economics of DMWTSD reusing in biomass plantations defined by several key inputs:

- Soil analysis costs
- Transportation costs
- Spreading (field) costs
- Revenues from biomass yield improvement
- Revenues from CO_2 removal

8.1 Costs related to DMWTSD recycling

SSD and national regulation on MWTS application in agriculture/forestry requires costly comprehensive analysis of soil heavy metals of each 5 ha of area considered for fertilization. Additionally, national regulation, in case of application of MWTS in biomass plantations, require implementation of soil and water monitoring program.

Taking into account rates of reuse of DMWTSD in biomass plantations and soil sampling and analysis costs – it is estimated that initial soil analysis and water monitoring analysis cost about **2,75 eur/t** of DMWTSD applied in biomass plantations (calculated as heavy metal analysis in soil – 85 eur/5ha sample and sample collection 50 eur/5ha plus heavy metal and nutrient analysis in monitoring water – 110 eur/50ha sample and sample collection 50 eur/50ha adjusted for 11 t/ha application rate).

Transportation costs of DMWTSD are dependent, whether DMWTSD are supplied packed in big bags or unpacked in container. If DMWTSD is supplied packed in big-bags, transportation volume is about 14,6 t/truck (NutriBiomass4LIFE case) and the average price per truck is about 200 eur/truck or 13,7 eur/t. Additionally we have to add big-bag (1,5 cub m) costs – *6* eur/t. Thus, total transportation costs of DMWTSD packet in big bag costs are **19,7 eur/ha**.

Costs of DMWTSD spreading in the biomass field are composed of unloading, spreading and disking (insertion into soil) costs. It is assumed, that 74 t /day of DMWTSD can be reused for fertilization with one set of machinery (two tractors). Spreading costs are composed of 3,03 l diesel /t of DMWTSD recycled (diesel price @ 1,5 eur/l), plus 300 eur / day / two tractor drivers wages and 200 eur /day tractor ((lease/maintenance) costs. Total DMWTSD spreading in biomass field costs are **11,3 eur/t** DMWTSD.

Overall costs for recycling of DMWTSD in biomass fields total about 33 eur /t DMWTSD, including soil analysis costs.

8.2 Revenues from biomass yield improvement

Biomass yield improvement estimations while using DMWTSD as fertilizer is not yet finally defined and require further measurements and estimations. NutriBiomass4LIFE biomass yield improvement measurements were performed during 3-year period for hybrid poplar fields and biomass yield improvement by 17% was recorded using 19 t/ha of DMWTSD. It was also recorded that biomass yield improvement decreases over the time, therefore, further research is needed over full rotation of poplars to estimate full impact of fertilization over biomass yield.

Calculations of the revenues from biomass yield improvement due to fertilization with DMWTSD are based on the following assumptions:

- Poplar plantations are established for the rotations of 20 years.

- Recycling of DMWTSD in newly established poplar plantations – two times per one rotation (total 22 t/ha) – increases poplar yield by 17%.
- The assumed prices for poplar wood are assumed at 30 eur/cub m for energy wood, at 40 eur/cub m for pulpwood/sawlogs and 60 eur/cub m for veneer logs at final harvest in year 20.

It is estimated that the Net present value (discounted @9,5%) of additional revenues due to biomass yield improvement while fertilizing with DMWTSD is 836 Eur/ha or **38 Eur/t of DMWTSD** applied for fertilization.

8.3 Revenues from CO_2 removal

As the world faces existential climate crisis, more and more businesses are committing to climate neutrality goals. Fast developing technologies outline promising tendencies towards substantial reduction of CO_2 emissions, nevertheless some of such technologies will be too expensive or even not available to eliminate all the CO_2 emissions. Therefore, CO_2 removal activities may come to assist businesses to achieve their carbon neutrality goals, especially related to scope three emissions.

Today exist several global possibilities to benefit from carbon removal activities and issue of carbon credits, associated with afforestation, including establishment of biomass plantations. The most globally recognised and reliable carbon removal certification schemes include VERA and Gold Standard.

In 2023 EU Commission came with Carbon Removal Certification Framework (CRCF) proposal, which targets to regulate carbon removal activities on the EU level and potentially open possibilities to businesses/farmers/forest owners to cash out from carbon removal activities. Although CRCF include carbon farming activities, still it is not yet clear whether biomass plantations establishment for DMWTSD will be eligible to issue carbon credits under CRCF, because it is not yet defined whether what will be considered agricultural or forestry activity.

Revenues from CO_2 removal may be associated with the establishment of the new biomass plantations and DMWTSD recycling in them to increase biomass yields and soil organic ccarbon. Fertilization with DMWTSD of existing biomass plantations may be considered for carbon removal activities in relation to increased biomass yield on existing plantations under forest management improvement methodologies, but forest management improvement methodologies are much more complicated and expensive to be engaged, therefore it is not assumed, that revenues from CO_2 removals will be generated from fertilization with DMWTSD of already existing biomass plantations.

Calculations of the CO_2 removals associated with the establishment of the new biomass plantations (i.e. afforestation) and DMWTSD recycling in them to increase biomass yields are based on the following assumptions:

- Recycling of DMWTSD in newly established poplar plantations – two times per one rotation (total 22 t/ha).
- Poplar plantations are established for the rotations of 20 years and grown at least for two rotations.
- Carbon credits are gained on the 17% increased biomass yield due to fertilization, or 34 carbon credits per ha or 1,5 carbon credit per 1 t of DMWTSD fertilized.

- Carbon credits are gained over first 13 years of biomass plantations establishment.
- The price for carbon removal is assumed at 30 eur/t CO_2

It is estimated that the Net present value (discounted @9,5%) of CO_2 removals due to biomass yield improvement while fertilizing with DMWTSD is **22Eur/t of DMWTSD** applied for fertilization.

Table 8-1. Calculation of NPV of CO_2 removals due to biomass yield improvement while fertilizing with DMWTSD

	year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10	year 11	year 12	year 13
Accumulated CO_2 removals, not fertilized, tCO_2/ha	0,0	0,0	1,3	7,0	19,6	39,1	64,1	93,0	124,3	156,8	179,3	201,6	209,6
Accumulated CO_2 removals due to yield increase after fertilization, tCO_2/ha	0,0	0,0	0,2	1,2	3,3	6,6	10,9	15,8	21,1	26,6	30,5	34,3	35,6
Annual CO_2 removals due to yield increase after fertilization, tCO_2/ha	0,0	0,0	0,2	1,0	2,1	3,3	4,3	4,9	5,3	5,5	3,8	3,8	1,4
Annual CO_2 removals due to yield increase after fertilization, tCO_2 / t DMWTSD	0,0	0,0	0,0	0,0	0,1	0,2	0,2	0,2	0,2	0,3	0,2	0,2	0,1
Annual revenues from CO_2 removals due to yield increase after fertilization, EUR/ t DMWTSD	0,0	0,0	0,3	1,3	2,9	4,5	5,8	6,7	7,2	7,5	5,2	5,2	1,8
NPV, EUR/ t DMWTSD	€22,4												

8.4 Financial result of the DMWTSD recycling in biomass plantations activity

Proposed CE model has a long economic horizon (20 year rotation). Fertilization with DMWTSD costs typically are incurred at the beginning of the cycle, while major revenues from yield increase can be expected at the end of the cycle - after 20 years only.

Overall costs for recycling of DMWTSD in biomass fields total about 33 eur /t DMWTSD, while major revenues from sales of increased biomass yield (38 Eur/t of DMWTSD, discounted) are expected only after the year 20. Although, discounted revenues from sale of biomass outweigh initial (fertilization) costs, but very long horizon between investment and revenues make such investment risky and not attractive for farmers and landowners. Additional revenues from CO_2 removal due to biomass yield improvement while fertilizing with DMWTSD is **22Eur/t of DMWTSD** may improve attractiveness to use CE model in biomass growing if CO_2 removal activities will be able to benefit financially from fast development of voluntary carbon markets and will not be limited by upcoming EU regulation (CRCF).

Financial calculations show that revenues from biomass yield increase due fertilization with DMWTSD may outweigh initial (fertilization) costs, but because of very significant time span between initial investment outflow and final revenue inflow, full or partial compensation of DMWTSD recycling costs is needed to make CE model economically attractive to farmers and forest owners.

9 Carbon footprint

Carbon footprint of DMWTSD recycling in CE model consists of several key elements:

- Transportation of DMWTSD from biomass boiler to DMWTSD recycling locations
- Application of DMWTSD in biomass plantations
- Management / supervision

- Replacement effect of nutrients (negative emissions)
- Biomass yield improvement (negative emissions)
- Soil organic carbon improvement (negative emissions)

9.1 Transportation carbon footprint

Carbon footprint of DMWTSD transportation form municipal wate-water treatment plants to biomass fields for recycling is based on the following assumptions:

- Long-haul trailer CO_2 emissions – 57g CO_2 per t km
- Actual weight of DMWTSD transported from municipal waste-water treatment plants to particular biomass plantation locations for reusage in biomass plantations, in tons
- Distance from VV and other municipal wate-water treatment plants to locations of particular biomass plantation for reusage in biomass plantations

It is estimated that carbon footprint from DMWTSD transportation form municipal wate-water treatment plants to biomass fields for recycling in biomass plantations during NutriBiomass4LIFE project implementation **equalled to 100,9 tCO_2.**

Table 9-1. Nutribiomass4LIFE carbon footprint from transportation DMWTSD

items		DMWTSD, dmt	DMWTSD, actual t	CO_2 footprint, t CO_2
Long-haul trailer CO_2 emission factor, g CO_2 /t km	57			
TOTAL		**16500**	**17003**	**100,9**

The key factor in reducing CO_2 emissions from transportation of DMWTSD is reducing distance to biomass fields from municipal waste-water treatment plants and switching to carbon neutral fuels.

9.2 Carbon footprint of application of DMWTSD in biomass plantations for fertilization purposes

Carbon footprint of application (fertilization) of DMWTSD in biomass plantations depends on the diesel fuel consumed by agricultural machinery and is based on the following assumptions:

- Average 17,6 t/ha DMWTSD applied during NutriBiomass4 LIFE project (current recycling is (11 t/ha of DMWTSD).
- 4,5 ha /day of biomass plantations fertilized with one set (two machines) of machinery.
- 74 t /day of DMWTSD used for fertilization with one set of machinery.
- Diesel fuel consumption is 14 l/h per one machine (tractor) working 8 hours.

It is estimated that carbon footprint of application (fertilization) of DMWTSD in biomass plantations for recycling during NutriBiomass4LIFE project implementation **equalled to 133,9 tCO2.**

Table 9-2. Nutribiomass4LIFE carbon footprint from application of DMWTSD in biomass plantations

	diesel l/dmt DMWTSD	DMWTSD, dmt	CO2 footprint, t CO2
1l diesel CO_2 emission factor, kg CO_2 /l	2,68		
Loading-unloading and disking	1,51	16500	66,9

Spreading of DMWTSD	1,51	16500	66,9
total	**3,03**	**16500**	**133,9**

Agricultural operations have significant carbon footprint due to high diesel consumption. This carbon footprint can be reduced by switching to renewable fuels. CO_2 footprint of application of DMWTSD in biomass plantations also depends on DMWTSD application rate (dmt/ha) – after changes in national legislation (LAND20-2001) when fertilization rate was reduced to 11 dmt/ha in biomass plantations, consequently CO_2 footprint will increase as more working hours will be needed to spread the same volume of DMWTSD.

9.3 Supervision of DMWTSD recycling

Carbon footprint of DMWTSD recycling supervision was calculated based on car fuel consumption, while travelling for supervision to DMWTSD recycling sites.

Table 9-3. Nutribiomass4LIFE carbon footprint from supervision of DMWTSD recycling in biomass plantations

	fuel CO_2 footprint, kg CO_2/l	fuel consumption, l/100km	travel distance, km	CO_2 footprint, t CO_2
Trips to recycling locations with petrol cars	2,3	8	7200	1,3
Trips to recycling locations with diesel cars	2,68	15	16272	6,5
Total			**23472**	**7,9**

9.4 Nutrient replacement effect

DMWTSD contain nutrients, from application of which in biomass plantation, negative CO_2 footprint can be recorded from nutrient replacement activities. Two major nutrients, which are abundant in DMWTSD are nitrogen (N) and phosphorus (P) and mineral nitrogen (N) fertilizers have the most significant negative carbon footprint from nutrient replacement effect.

Table 9-4. Nutribiomass4LIFE carbon footprint from nutrient replacement using DMWTSD

Replacement of nutrients	Fertilizer production footprint t CO2 eq/t nutrient	tons reused	CO2 emission avoiding by replacement, t CO2
Total nitrogen (N) ref Urea	3,6	794,81	-2861,3
Total phosphorus (P) ref P2O5	0,56	361,34	-202,3
Total potassium (K) ref K2O	0,43	54,73	-23,5
Total calcium (Ca) ref CaCO3	0,10	989,96	-96,8
total			**-3184,0**

Total negative CO_2footprint from nutrient replacement from NutriBiomass4LIFE DMWTSD recycling in biomass plantation activity implementation **equalled to minus 3184 tCO2.**

9.5 Biomass yield improvement effect

Biomass yield improvement while applying DMWTSD has a strong negative carbon footprint value, as it is associated with CO_2 removal and storage in biomass increment (sequestration). As presented in the table 9.5-1 bellow CO_2 removal is dependent on the following factors:

- Type of biomass crops involved – poplars, hybrid aspen and willows were fertilized with DMWTSD and all of them had different yield patterns and increments during NutriBiomass4LIFE project.
- Year of establishment – according to the growth curve, older plantations have respectively much higher annual yield increment, therefore, yield increase due to fertilization is also much higher than comparing to young plantations.
- Year of fertilization – during implementations of NutriBiomass4LIFE project biomass plantations were fertilized in different years (from year one to four of the project), and yield improvement was calculated from the year of fertilization to the project end, therefore, those plantations which were fertilized at the beginning of the project had a higher CO_2 removal capacities due to biomass yield improvement comparing to the fertilized at the end of the project.
- Survival rate – tree survival rate has a direct impact over plantations biomasses yield and CO_2 removal capacities.
- Overall biomass yield – while calculating carbon removal, biomass yield per fertilized plantation is assumed for the period post fertilization with DMWTSD to the project end. Initially fresh above ground biomass without leaves, based on biomass yield measurements from project's C2 action, is deployed based on biomass crop type and age; later it is converted to total fresh biomass (including below ground biomass) based on coefficients developed during project's C2 action.
- Yield increase due to fertilization – yield increase due to fertilization with DMWTSD coefficients developed during project's C2 action are deployed based on biomass crop type, age and fertilization year.
- Dry biomass and CO_2 coefficients – based on coefficients developed during project's C2 action fresh biomass is converted to dry biomass and 0,48 coefficient applied to convert dry biomass to carbon (C); later 3,67 coefficient is applied to convert C to CO2.

Estimations of carbon footprint from biomass yield improvement effect due to fertilization with DMWTSD during implementation of the project NutriBiomass4LIFE from different biomass plantations, are presented in the table 9.5 bellow and equalled to **minus 5085 tCO_2.**

Table 9-5. Nutribiomass4LIFE carbon footprint from biomass yield improvement effect due to fertilization with DMWTSD

Address	Land plot Unique No.	Fertilization area, ha	type of crop	Year of establishment	Year of fertilization	Survival, %	Total ABG without leaves yield after fertilization,	Yield increase due to fertilization, %	ABG without leaves yield due to fertilization, fresh t /ha	Total biomass yield due to fertilization			Total CO_2 removed due to fertilization, t CO_2 / fertilized area
										fresh t/ ha	fresh t/ fertilized area	dry t / fertilized area	
TOTAL		**937**							**197,8**	**305**	**619**	**2886**	**-5085**

9.6 Soil organic carbon improvement

Fertilization with DMWTSD has a clear positive effect on soil organic carbon (SOC) increase as DMWTSD itself is very rich in organic carbon. This SOC increase is calculated as SOC increase due to adding of organic carbon from DMWTSD to the soil, which is presented in the table 9.6 bellow and equals to **minus 14443,4 tCO_2.**

Table 9-6. Nutribiomass4LIFE carbon footprint from calculated SOC increase due to shift of organic carbon from DMWTSD

Address	Land plot Unique No.	Fertilization area, ha	Average fertilization rate t/ha	Organic carbon content, %	Organic carbon input into soil, t	CO_2 footprint, t
TOTAL		**936,9**			**3935,5**	**-14443,4**

Alternatively, assessment of SOC changes after application of DMWTSD and from growing of trees on agricultural land can be measured by taking soil samples and analysing actual ex—ante and ex-post SOC concentrations in soil. This method is widely recognized scientifically as a reliable path to prove SOC changes, but has several shortages:

- The changes in SOC, especially accumulations, take a very long time – tens or even hundreds of years, therefore SOC measurements in short intervals after one or several years cannot yield result, yet.
- In order to evaluate SOC changes ex-ante and ex-post soils samples have to be collected and analysed. In Lithuania according to soil sampling methodology, each soil sample for laboratory analysis is made from a mix of 20 sub-samples collected within 100 m path on the same soil type. GPS tracking is employed for ex-ante sampling, to follow the same track. Nevertheless, when the ex-post samples are collected, it is not possible to follow exactly the same rout as in the areas with significant soil variations even half a meter variation from initial track can yield different results. This is particularly problematic, when the soil is not homogeneous, and has a huge variation in SOC – as in case of NutriBiomass4LIFE biomass plantations, where soil variation even on the same land plots is very significant.
- Organic and mineral-organic soils have to be excluded from the prevailing mineral soils as SOC concentrations in organic and mineral-organic soils is many times higher than in mineral soils and organic and mineral-organic soils typically emit CO_2 regardless of soil management practices.

SOC accumulations in soil, t ha^{-1}, are calculated according the following formula:

$$SOC = SOC_{conc} \times TS \times SG, \quad (1)$$

Where:

SOC – Organic carbon accumulation in soil, t ha^{-1};

SOC_{conc} – Soil organic carbon concentration, %;

TS – soil density, g cm^{-3} for different types of soil; (s – 1,35, ps – 1,40, p-p_1 – 1,45, p_2-m – 1,55,

pv – 1,10, d – 0,65–0,95)
SG – humus rich topsoil layer, cm (for mineral soils – 25–28 cm, for organo-mineral soils – 34–35 cm, for organic soils – 50–100 cm).

Bellow in the Table 9.7 carbon footprint assessment based on laboratory analyses of SOC accumulations due to fertilization with DMWTSD is presented. While calculating carbon footprint assessment based on laboratory analyses of SOC accumulations due to fertilization with DMWTSD the following adjustments were made:

- Soils, which do not had SOC_{conc} analysis data were excluded from estimations.
- Organic and organic-mineral soils analysis data were excluded from estimations – 38 soil samples were excluded for that reason;
- Mineral soils with unreasonably high SOC_{conc} decrease (over 30% decrease) were excluded from estimations – 24 soil samples were excluded for that reason;
- prevailing 1,45 g cm^{-3} soil density of the mineral soils for the SOC analysis was used for calculation of carbon footprint

Table 9.7 reveals that adjusted carbon footprint assessment based on analyses of SOC accumulations due to fertilization with DMWTSD included 449,3 ha analyses area, which is after adjustments totalled 48% of total fertilized area. Consequently, carbon footprint from smaller analyses area has to be smaller. Nevertheless, adjusted carbon footprint assessment based on analyses of SOC accumulations due to fertilization with DMWTSD totalled **minus 4647,1 tCO_2 (or minus 9681 tCO_2,** adjusted for the whole fertilized area) which is **67%** of SOC increase, which is calculated due to adding of organic carbon from DMWTSD. Considering the above listed considerations, we think that SOC increase calculated as due to adding of organic carbon from DMWTSD is a more reliable SOC increase data in short term.

Table 9-7. Nutribiomass4LIFE carbon footprint according to analyses of SOC accumulations due to fertilization with DMWTSD

Address	Land plot Unique No.	Fertili-zation area, ha	Number of all soil samples	Adjusted number of soil samples for CO_2 footprint estimations	Adjusted fertilization area for CO_2 footprint estimation	Adjusted average ex-ante SOC_{conc}, %	Adjusted average ex-post SOC_{conc}, %	Changes in SOC, t	CO_2 footprint, t
TOTAL		**936,8**	**146,0**	**85,0**	**449,3**	**1,5361**	**1,6138**	**1266,2**	**-4647,1**

9.7 Carbon footprint balance

Calculated CO_2 footprint balance from NutriBiomass4LIFE DMWTSD recycling in biomass plantation action implementation **equalled to minus 22469,7 tCO_2** and was composed of:

- CO_2 footprint from DMWTSD transportation form waste-water treatment plants to biomass fields for recycling in biomass plantations, which equalled to **100,9 tCO_2**.
- CO_2 footprint from application (fertilization) of DMWTSD in biomass plantations, which equalled to **133,9 tCO_2**.
- CO_2 footprint from supervision of DMWTSD recycling in biomass plantations, which equalled to **7,9 tCO_2.**

- Negative CO_2 footprint from nutrient replacement from DMWTSD recycling in biomass plantation activity implementation, which equalled to **minus 3184 tCO_2**.
- Negative CO_2 footprint from biomass yield increase due to DMWTSD application in biomass plantations, which equalled to **minus 5085 tCO_2**
- Negative CO_2 footprint from biomass SOC increase due to application of DMWTSD in biomass plantations, which equalled to **minus 14443,4 tCO_2.**

10 Policy

Through the adoption of European Green Deal, CE model developed by NutriBiomass4LIFE is coherent with multiple EU and national policies and legal regulations. Nevertheless, we encountered some incoherencies among several policies in particular what relates to prioritising of MWTS usage in circular way over incineration.

10.1 Coherence with EU policies

10.1.1 Sewage sludge directive

NutriBiomass4LIFE CE model strongly relied on SSD, as it should ensure protection of the environment, and, in particular, of the soil and water, when sewage sludge is used in agriculture. DMWTSD, which was used during implementation of NutriBiomass4LIFE project, is considered as a waste, and was used to fertilize biomass plantations in full compliance with SSD.

In particular, the following regulations of SSD applied to NutriBiomass4LIFE project:

- Usage of MWTS in agriculture – DMWTSD both was used in agriculture (short rotation plantations established on agricultural land) and forestry (established forest plantations only), and in both cases regulations of SSD were followed, although SSD does not regulate usage of MWTS in forestry.
- Definition and requirements on treatment of sludge, as the SSD requires sludge to be treated before spreading on land - the DMWTSD of VV undergoes thermo-hydrolysis and anaerobic treatment before application in biomass plantations.
- Compliance to concentration of heavy metals in soil – ex-ante soil analysis was performed for each respected 5 ha area of NutriBiomass4LIFE biomass plantations to ensure compliance to SSD.
- Definition of sludge quality (contamination limits) – VV and other municipal waste-water treatment plants regularly conducted chemical analysis of their MWTS to ensure sludge quality compliance to heavy metal limits to be allowed for usage in agriculture.
- Compliance to annual quantities of heavy metals which may be inputted into agricultural soil – based on soil analysis and MWTS analysis NutriBiomass4LIFE project ensured compliance to annual quantities of heavy metals which may be introduced into agricultural soil.
- Compliance of other restrictions on the usage of MWTS in certain times or areas - NutriBiomass4LIFE respected other requirements of SSD to ensure that the risk of leakage of contaminants into ground and surface waters is minimised.

Although legal basis of SSD is related to the functioning of the EU internal market, MWTS is purely a local product (type of waste), which due to low economic value and high transportation costs have to

be managed nationally and even better locally close to production source (municipal waste-water treatment plant). NutriBiommass4LIFE demonstrated, that sewage sludge can be successfully used in circular way even for large municipalities, where large areas for fertilization are needed. In this case to meet MWTS recycling demand of large municipal wastewater treatment plants the effective distance from large municipal waste-water treatment plant to nutrient reusage fields may be expanded from traditional 50 km (the distance is reasonable to smaller municipal wastewater treatment plants) to 100 km.

10.1.2 Circular economy and nutrient recovery

The new Circular economy action plan ((COM(2020) 98), which was adopted on 11 March, 2020, is one of the core stones of the European Green Deal. While building on circular economy actions implemented since 2015, the new Circular economy Action Plan provides a future-oriented agenda for achieving a cleaner and more competitive Europe, while reducing the negative impacts of resource extraction and use of the environment.

Circular economy Action Plan outlines wastewater and sewage sludge as the core objects for facilitating recovery of nutrients by contributing to EU aim to reduce its dependency on imports of nutrients from third countries, moving towards energy efficiency and carbon neutrality. This can be achieved by removing nutrients from wastewater and sludge and making sewage sludge for direct reuse in agriculture through the development of EU Integrated Nutrient Management Plan.

In March 2023 the new Critical Raw materials Acct was announced, in which phosphate rock and phosphorus are on the EU's critical raw materials list, which means incentives for recovering phosphorus from wastewater and sewage sludge and direct reusage of sewage sludge, should be increased. In addition to phosphorus, nitrogen recovery from wastewater and sewage sludge is very important not only from the point of nutrient recovery, but even more important from carbon neutrality targets, as GHG emission from nitrogen production processes is many times higher than from production of phosphorus fertilizer.

The landfilling Directive (1999/31/EC), which aims at reducing the amount of waste, which is landfilled, contributes towards decrease of landfilling of sewage sludge towards increase in sewage sludge usage in agriculture and in for energy recovery (incineration).

The Waste Framework Directive (2008/98/EC) sets a waste hierarchy requiring to prioritise sewage sludge reusage in agriculture / forestry and nutrient recovery over energy recovery or disposal. The Waste Framework Directive allows to adopt national 'end-of-waste' criteria which recognise the status of sewage sludge digestate and/or of compost as products and no longer as a waste, that may facilitates sewage sludge reusage in agriculture. The Fertilising Product Regulation 2019/1009 establishes end-of-waste criteria for EU fertilising products containing certain materials derived from sewage sludge as well. However, under such criteria only part of sewage sludge may switch from waste to fertilizing product classification. Still, a major part of sewage sludge may be used in agriculture under the status of waste, which imposes stricter requirements and additional costs related to its treatment, transportation, application to soil and reporting.

NutriBiomass4LIFE project developed model where processed sludge (dried digestate) is used as a waste in non-food crop production in full compliance with SSD, which ensures full nutrient (nitrogen, phosphorus and carbon) recovery and usage in circular way.

10.1.3 Zero pollution policy

Zero Pollution Action Plan was developed under the European Green Deal vision to achieve a zero pollution by 2050. Zero Pollution Action Plan aims at preventing pollution for air, water and soil and achieving levels no longer considered harmful to health and natural ecosystems and at securing soil quality.

The EU Soil Strategy for 2030, adopted in 2021 as part of the European Green Deal, provides the framework towards protecting and restoring soils, and ensuring that they are used sustainably. The strategy replaced the former Thematic Strategy for Soil Protection. The EU soil strategy refers to the evaluation of the SSD, since SSD can contribute to sustainable use of soil, as it outlines quality standards for agricultural soil at the EU level.

In the Soil strategy, the EU committed to adopt the new Soil Health Law to protect and restore soils and ensure that they are used sustainably, and in July 2023 a legislative proposal for a Directive on Soil Monitoring and Resilience (the Soil Monitoring Law) was proposed. The renaming from Soil Health to Soil Monitoring Law indicates that the focus has switched to observing soil health rather than ensuring its health improvement not including legally binding targets or requiring mandatory plans. In particular, Soil monitoring law outlines review of SSD related to inclusion of microplastic pollution monitoring from sewage sludge, also puts heavy emphasis on organic soil carbon improvement, where direct application of sewage sludge may contribute to the solution.

Sewage sludge not only enhances fertility of soils through its organic and nutrient content, but it can also foster soil health improvement through soil structure improvement and soil organic carbon (humus) accumulation, which implements soil sustainability and climate neutrality targets. Lime-treated sludge can also help reduce the acidity of agricultural soils. With expansion of anaerobic digestion practices in sludge management due to implementing renewable energy and climate polices, a more sewage sludge in a form of digestate will be available for fertilization purposes. Sludge digestate has numerous advantages over low processed sewage sludge:

- Sewage sludge digestate-derived fertilizing products have a high nitrogen availability which makes them efficient alternatives to synthetic fertilisers.
- Sewage sludge digestate use is contributing to maintain soil fertility in contrast to using synthetic fertilisers. Sewage sludge digestate contains significant concentrations of humus-effective carbon and in long term it is a key in maintaining soil fertility as well as soil microbiota to ensure high crop yields and sustainable land management.
- Dry sewage sludge digestate, as a more stable form of organic fertilizer, has a strong potential to contribute to reduction of nutrients losses through the leaching in water and air.
- Sewage sludge digestate is a circular product and can displace GHG emissions and natural gas consumption inherent to the production of synthetic fertilisers.

In October 2023, the Council adopted the proposal on the new Urban Waste Water Treatment directive, that sets requirements form the collection and treatment waste water in the EU to protect the environment from the adverse effect of discharges of urban waste water. Under Article 20 (former 14) of the UWWTD the sewage sludge has to be treated, recycled and recovered whenever appropriate in accordance with the waste hierarchy as defined as defined in Article 4 of Waste Directive 2008/98/EC and the actions to better monitor and reduce pollution at source from upstream and non-domestic discharges have to be introduced to help improving the quality of the sludge produced and ensure its safe use in agriculture. Additionally, the new UWWTD orders to ensure a proper and safe recovery of nutrients, including the critical substance phosphorus and nitrogen, from the sludge, therefore minimum recovery rates should be defined at the EU level.

Upstream wastewater discharge monitoring is an essential to reduce risks of contamination in wastewater and sewage sludge. The new UWWTD introduces principles polluter pays for certain type of contaminants – like microplastics. Besides empowering modern water cleaning technologies to minimize nitrogen and phosphorus content in discharged water to the environment, wastewater treatment plants will need to introduce upstream monitoring systems to reduce contaminants which are not possible to clean (e.g. heavy metals, microplastics) at waste water treatment plants. Pathway to sewage sludge incineration limits wastewater treatment plant motivation and efforts to monitor and manage upstream contaminant reduction, as heavily contaminated sludge can be incinerated without limitations. Unfortunately, not all wastewater contaminants end in sewage sludge – significant part (depending on the type of contaminant) is discharged to the environment with cleaned wastewater from wastewater treatment plants (at low concentrations but with many times higher discharged water volume comparing to sewage sludge volume).

NutriBiomass4LIFE project contributes at implementation of Zero Pollution policy, by complying to SSD regulation, that prevents harmful effects of sewage sludge usage on soil, vegetation, animals and people, in general and specifically as regards prevention of pollution by heavy metals. Additionally, by switching DMWTSD towards non-food crop fertilization, NutriBiomass4LIFE CE model eliminates all risks related to contamination of food chain and risks to human health.

10.1.4 EU energy and climate policies

The EU energy policy targets to reduce supply dependency from imports from outside the EU, while moving towards a low-carbon economy.

RED II and revised by RED III set overall share of renewable energy and share of renewable energy in certain sectors. In March 2022, in its REPowerEU Communication, the Commission outlined a plan to advance these targets to well before 2030 in view of increasing Union's independence from Russian fossil fuels and reduce EU demand for Russian gas.

All sewage sludge, under current EU legal framework, is considered as renewable energy source and can contribute to renewable energy in two ways: production of biogas (biomethane) through anaerobic digestion and heat/power production through incineration.

RED II /RED III and REPowerEU Communication pay special emphasis for sewage sludge processing by anaerobic digestion and production of biomethane for transportation needs. RED II /RED III prioritizes sewage sludge usage as a feedstock for the production of biogas for transport and advanced biofuels

and sets its contribution to a share of final consumption of renewable energy in the transport sector double to sewage sludge energy content (Annex IX).

Anaerobic digestion is a growing sewage sludge treatment method as it allows the production of biogas concomitantly with sludge use in agriculture: while the process generates biogas the resulting digestate can be used on land as fertilizer in parallel. The key limitation of anaerobic digestion treatment is heavy metals concentrations in sewage sludge which are not decreased by the process and may be limiting factor categorizing sewage sludge digestate as a fertilizing product. Nevertheless, as it is demonstrated by Nutribiomas4LIFE project, sewage sludge digestate can be used as fertilizer in biomass plantations based on SSD regulations as a waste without harming environment and people.

There are two major types of energy recovery from sewage sludge technologies, which differ in their approach to compliance to Circular economy policy and the principle of the waste hierarchy established by Waste Framework Directive. The first one – a simple co-incineration of sewage sludge in waste incineration plants or cement production facilities without nutrient recovery.

The second one – more modern, mono-incineration of sewage sludge with potential phosphorus recovery from ashes. The last one technology is employed by some European countries (Germany, Netherlands, Austria) that implement policies that discourage the application of sludge to land and/or encouraging phosphorus recovery from sewage sludge. Phosphorus recovery from sewage sludge ash is currently more expensive to implement and operate compared to the revenues generated from selling fertilisers, which limits the potential for widespread implementation. This treatment route also does not allow for the recovery of the organic nitrogen and organic matter contained in the sludge, which is provided by direct fertilization option with sewage sludge.

The Energy policy directing sludge to incineration (or co-incineration which aims only at energy recovery) for heat / power production impedes the recovery of the organic nutrients in sludge. RED II /RED III define that the principle of the circular economy and the principle of the waste hierarchy established in Directive 2008/98/EC should be respected in national legislations to produce bioenergy, but limitations are imposed only on developing support schemes for bioenergy production.

Implementation of NutriBiomass4LIFE project showed, that there is major incoherence related to final sewage sludge application between Circular economy / nutrient recovery policies with EU energy and climate policies. There is a lack of unified strategy to ensure that sewage sludge governance also encourages circularity, recovery or recycling.

Although RED II /RED III prohibits development of support schemes for bioenergy production that disregard principle of the circular economy and the principle of the waste hierarchy established in Directive 2008/98/EC, EU Emission Trading Scheme indirectly subsidizes sewage sludge incineration without nutrient recovery over reusage of sewage sludge on land or nutrient recovery.

Waste incineration plants, being a subject of EU Emission Trading Scheme, have to pay for their CO_2 emissions generated from waste incineration. As sewage sludge is classified as renewable energy source, using sewage sludge to produce energy allows to reduce emissions allowances needed. It is estimated that due to saving on emission allowances, waste incineration plant can save from 0,8 (in case of DMWTSD of VV) to 1,4 (in case of DMWTSD of KV) emission allowances per one tone of

incinerated DMWTSD, or 55-100 eur / dmt of DMWTSD. Sewage sludge digestate has lower carbon content per dmt, therefore it has lower energy content per dmt comparing to unprocessed sludge. Additionally, depending on anaerobic digestion technologies employed, substantially different volumes of biogas can be produced from the same dmt of unprocessed sewage sludge. Consequently energy (and organic carbon) content in processed sewage sludge digestate may differ even two times.

Higher financial benefits (profit) can be achieved by cement production plants as cement producers receive free emission allowances, therefore they are able to sell saved emission allowances at a profit. Even on 25 April 2023 the Council adopted the reform of EU Emission trading System with gradual phase out of free emission allowances from 2026 to 2034. The reform foresees that issue of free emission allowances to all ETS sectors, which currently receive free emission allowances, will be gradually (with exception of cement and fertilizer industries) phased down starting from 2026, making sewage sludge incineration at cement plants still financially attractive option.

Overall, the carbon footprint for the different sludge management routes differs. The direct use-on-land of untreated, lime stabilised sewage sludge and in particular sludge processed by anaerobic digestion have a strong net negative carbon footprint and can therefore act as a climate change mitigation strategy, in contrast to sludge incineration pathways.

NotriBiomass4LIFE model, which used sewage sludge, processed by anaerobic digestion, has the biggest negative carbon footprint due to combination of multiple factors: (1) sequestration of CO_2 in soil (adding organic carbon to soil), (2) potential to substitute synthetic fertilizers, produced through energy-intensive processes, (3) CO_2 sequestration in biomass of trees due to increased yields from applications of nutrients from sewage sludge and (4) replacement of fossil fuels by producing biogas through anaerobic digestion sludge processing. Unfortunately, Emission trading system through free emission allowances subsidizes the worst sewage sludge management pathway - incineration at cement production plants.

On 21 November, 2023 European Parliament adopted Carbon Removal Certification framework (CRCF). The aim of the proposed regulation of certification framework for carbon removal is to facilitate the deployment of high-quality carbon removals through a voluntary EU certification framework with high climate and environmental integrity. Carbon removals also constitute a new business model in the voluntary carbon market. This initiative is instrumental in ensuring the soil's capacity to absorb and store carbon and promoting other carbon farming activities (including tree planting) to sequester and store carbon.

Carbon Removal Certification framework defined four different types of activities covered by the certification framework, that will be able to benefit from their contribution to meet EU climate targets: carbon removal, carbon farming sequestration, carbon farming emissions reduction and carbon storage in products. Carbon Removal Certification framework is expected to be implemented by 2030, but it may finally set framework for NutriBiomass4LIFE model to benefit from its contribution to climate targets and to equal ground with sewage sludge incineration alternative. It is clear that NutriBiomass4LIFE CE model has clear negative carbon footprint, but benefitting from Carbon Removal Certification framework will depend on developed carbon removal methodologies, which already posing certain questions: whether short rotation trees on agricultural land will be considered forestry

or agricultural activity, whether there will be methodologies for carbon storage in soil while applying biosolids to soil, whether sewage sludge biosolids will be included in carbon removal certification, etc.

Introduction of the new Urban Waste Water Treatment directive and call to the Commission to set legal background to ensure a proper and safe recovery of nutrients (phosphorus and nitrogen) from sewage sludge by setting minimum recovery rates at the EU level hopefully will clearly prioritize sewage sludge reuse and recycling over incineration for energy purposes only. Introduction of obligations to reuse and recycle sewage sludge with removal of financial incentive to incinerate sludge without recycling option will change the flows of sewage sludge management and NutriBiomass4LIFE CE model will gain competitiveness over current incineration flows.

10.2 Coherence with national policies

NutriBiomass4LIFE CE model is fully coherent with national policies which are mainly facilitated by the key EU policies.

10.2.1 Implementation of EU Sludge directive

Implementation of SSD regulations related to application of sewage sludge on agricultural land is governed by "Rules of waste-water treatment sludge usage in fertilization and land reclamation LAND 20-2005" issued by the Minister of environment of the Republic of Lithuania.

LAND 20-2005 defines that processed sewage sludge can be used (1) in agriculture, (2) in woody biomass growing – short rotation plantations established on agricultural land and forest plantations and (3) in land reclamation and sets different requirement for each category of application regarding sludge quality criteria, fertilization rate, monitoring and permitting procedures.

NutriBiomass4LIFE follow the path of sludge usage in woody biomass growing – short rotation plantations established on agricultural land and forest plantations, which allows to use 11 dmt/ha of DMWTSD once in three years (appr. 3 times more than in agriculture) but requires more complicated permitting procedure and monitoring plan.

Comparing to SSD, Lithuania has much stricter regulation on heavy metal concentration limits when it is allowed to use sewage sludge in agriculture and biomass plantations as defined in table 10-1.

Table 10-1. Comparison of heavy metal limits (mg/kg) in sewage sludge according to SSD, LAND 20-2005 and Fertilizing products requirements

Heavy metal limits (mg/kg)	Cd	Cr	Ni	Cu	Pb	Zn	Hg	As
SSD	20-40		300-400	1000-1750	750-1200	2500-4000	16-25	
LAND 20-2005, I category	<1,5	<140	<50	<300	<140	<800	<1,0	
LAND 20-2005, II category	1,5-5,0	140-170	50-70	300-1000	140-150	800-2500	1,0-1,5	
Fertilizing products	<2,0	<70 and <2 (Cr VI)	50	<300	<120	<800	<1,0	<40

Sewage sludge of both I and II categories (LAND 20-2005) as a waste can be used for fertilization both in agriculture and biomass plantations, following the procedures defined in LAND 20-2005. Sewage sludge digestate or compost, which meets Fertilizing product criteria, can be excluded from waste category, and used as fertilizing product.

10.2.2 National regulation on circularity

Lithuania does not have its circular economy strategy and therefore there is no clear policy directing towards circular economy pathway.

Although Lithuanian Law on Waste management defines the same waste hierarchy requiring to prioritise sewage sludge reusage in agriculture / forestry and nutrient recovery over energy recovery or disposal (as in the EU Waste Framework Directive (2008/98/EC)), currently there is no other legislation which would oblige wastewater treatment plants to follow circularity path over incineration.

On July 3, 2020 Ministry of Environment issued new version of "Rules of waste-water treatment sludge usage in fertilization and land reclamation LAND 20-2005" regulation which came into force on January 1, 2021 and which had a clear shift towards circular economy prioritising sewage sludge usage in agriculture and biomass plantations. Based on the waste hierarchy requiring to prioritise waste management as defined by the Waste Framework Directive (2008/98/EC), it was defined that sewage sludge can be incinerated or used for landfill coverage only in case fertilization option is not available.

Unfortunately, this important legislative provision was not respected by wastewater treatment plants and sewage sludge was supplied for incineration disregarding fertilization availability. The election and the change of the Government and the new management of the Ministry of the Environment under the lobby of big company (cement producer) very quickly reversed circular economy pathway towards incineration economy. The legislation, that sewage sludge can be incinerated without phosphorus recovery only if fertilization option is not available, was abolished from June 14, 2021, and today in Lithuania sewage sludge incineration without phosphorus recovery is again treated equally in the pyramid of waste management as reusage (fertilization) or recycling of sewage sludge.

10.2.3 Pollution risk management

One of the primary tasks of LAND 20-2005 is to ensure that sewage sludge usage will be used on agricultural land and biomass plantations safe and with no harm for soil, water, animals, and humans.

One of the pollution prevention measures was to establish heavy metal concentration in sewage sludge limits, as it is outlines in table 10-1. Lithuania has established much stronger heavy metal limits compared to outlined in SSD, which significantly limits pollution risks.

Another pollution risk minimizing tool – regulation on sewage sludge application rate. According to LAND 20-2005 sewage sludge can be applied only once in three years both in agriculture and biomass plantations. In agriculture sewage sludge application is limited by nitrogen (140 kg/ha) and phosphorus (40 t/ha) limits. Based on nitrogen and phosphorus concentrations in sewage sludge it is estimated that on average 2-3 dmt/ha of sewage sludge can be applied in agriculture once in three years. In biomass plantations it is allowed to apply 11 dmt/ha of sewage sludge once in three years (or 3,6 dmt/ha/year on average). Existing high restrictions on heavy metal limits in sewage sludge and low application rates ensure were low risk for contamination and pollution. Based on LAND 20-2005 requirements and actual heavy metal concentrations in sewage sludge in Lithuania there is no risk that soil contamination limits set by SSD will ever be reached when regularly applying sludge to the soil. The same low risk situations exists regarding risk of leaching contaminants into water.

LAND 20-2005 sets environmental permitting and monitoring procedure. During implementation of Nutribiomass4LIFE, starting 2021 project permitting procedures were simplified - after regulation revision permitting is handled by Environmental Protection Agency with approval of monitoring plan by Lithuanian Geological service within shorter period. After revision since 2021, municipalities were relieved from permitting process with granting more active role in monitoring. While preparing fertilization plan for the environmental procedures, higher risk zones for leaching as defined in LAND 20-2005 must be excluded from fertilization area.

NutriBiomass4LIFE promotes sewage sludge usage in non-food biomass plantations according to special regulation defined in LAND 20-2025. LAND 20-2025 regulates, that soil and water monitoring plan has to be developed for fertilization of biomass plantations:

- To ensure concentration limits of heavy metals in soil are note breached – soil analysis has to be repeated before each following fertilization if initial soil analysis shows that concentrations of heavy metals exceed background (national average) concentrations in soil.
- To ensure concentration limits of heavy metals and macro nutrients (N and P) in drainage and ground water are note breached – water analysis has to be performed after each fertilization.

Water monitoring requirements for heavy metals in water were introduced since 2021 and are applied for biomass plantations fertilization only. NutriBiomass4LIFE water monitoring actions showed that there are low no risks associated with leakage of heavy metals in water form biomass plantations fertilized with sewage sludge if sewage sludge quality parameters and fertilization rate limits are respected.

The following modifications to water monitoring while fertilizing with sewage sludge would be reasonable:

- To cancel excessive and expensive requirements for heavy metal monitoring in water in biomass plantations – all the water monitoring analysis during NutriBiomass4LIFE project showed that heavy metal concentrations in water are even below detectable levels imposed for drinking water requirements.
- Instead of heavy metal monitoring in water, monitoring of macro nutrients fractions can be expanded by including nitrate nitrogen ($NO_{3\text{-}N}$) to unify the requirements for water monitoring in manure and sewage sludge while fertilizing agricultural crops and biomass plantations.
- To change requirement to perform ground water monitoring, if drainage system water monitoring is not available (there is no drainage system installed), to perform water monitoring by installing water collection lysimeters. Ground water monitoring is extremely expensive and is installed for monitoring of heavy pollution sources like higher risk for water pollution manufacturing facilities, petrol stations, etc. – up till now no one ground water monitoring system was installed for sewage sludge fertilization monitoring. Lysimeter monitoring systems are widely used in research and practical nutrient leakage monitoring.

10.2.4 Energy recovery from sewage sludge

After the first EU circular economy package was adopted in 2015, many EU countries started to slow down or even stopped investments into waste incineration. Contrary, initial Lithuania's investment

into waste incineration capacities were slow, but much accelerated after adoption of EU circular economy package. These latest investment into waste incineration in Lithuania were mainly driven by state - the state-controlled energy company got exclusive right to invest into waste incineration. In Lithuania waste incineration is still publicly presented as part of circular economy and waste incineration plants are presented as flagships of circular economy – a clear example of "green washing".

In 2020 big new waste incineration facilities started their operations in Lithuania - Kaunas Waste incineration plant and DMWTSD incineration at Akmene cement production plant. Additionally, in 2021 EU subsidised waste incineration plant started its operations in Vilnius. Today large waste incineration capacities and their extreme profitability in Lithuania are the key obstacle for moving towards circular economy. Extreme profitability (over 50% EBIDTA or even EBIT) of waste incineration business is mainly defined by monopolistic conditions, direct and indirect subsidies and long-term state policies not directed at promoting municipal waste sorting and recycling. Such a high profitability of waste incineration businesses means, that Lithuania, without proper regulation directing waste from incineration towards recycling or reuse, will not be able to meet its circular economy obligations.

The Law on Waste management classifies sewage sludge as biodegradable waste and Lithuanian Law on Renewable energy resources attributes biodegradable waste to biomass, from which renewable energy is produced. Therefore, sewage sludge is considered as renewable energy source both in terms production of biogas through anaerobic digestions and in terms of heat and power produced through incineration with or without nutrient recovery.

From 2020, after opening waste incineration facilities in Kaunas (waste incineration plant) and Akmene (cement producer), dry sewage sludge digestate was redirected to incineration facilities, primary at Akmene cement plant in the North of Lithuania. The key reason for incineration to be the most competitive for DMWTSD management option in Lithuania is that sewage sludge is classified as biomass, therefore sewage sludge incineration considered as carbon neutral energy production, that allows to save on Emission allowances – from 0,8 to 1,4 tCO_2 DMWTSD incinerated. As the majority of municipal waste (which also has about 50% (fresh weight) of biodegradable waste in it) is being incinerated, there is sufficient supply of municipal waste for waste incineration plants in Vilnius, Kaunas and Klaipeda, so today waste incineration plants are not willing to offer cheaper incineration prices comparing to municipal waste. But this situation will change in future if significant part of municipal waste, as required by EU regulation, will be redirected towards composting (biodegradable part) and recycling.

Cement producer can offer less expensive option for dry sewage sludge digestate management to waste-water treatment plants due to policies to subsidise incineration. By incinerating dry sewage sludge digestate cement producer replaces coal burning and saves appr. from 1,6 (in case of DMWTSD of VV) to 2,8 (in case of DMWTSD of KV) emission allowances per one tone of replaced tone of coal, or 110-200 eur t/ replaced coal. Additionally, cement producer on the EU level are provided with free emission allowance to cover their CO_2 emissions (i.e. cement producers as the biggest CO_2 emitters are exempted from principle "polluter pays"). By incinerating sewage sludge cement producers are capable directly to profit from selling of free emissions allowances saved by incinerating sewage sludge

and that provides waste incineration with solid financial competitive advantage, comparing to sewage sludge recycling or reusing options.

Comparing carbon footprint, sewage sludge reusage in offered NutriBiomass4LIFE CE model has much bigger negative carbon footprint than incineration at cement production facility. In case of incineration of sewage sludge at cement production facility, cement producer can directly benefit from lower CO_2 emissions comparing to coal usage through EU subsidy (sale of free emission allowances). In case of sewage sludge usage in much more carbon negative pathway - in fertilization of biomass plantations, financial benefit is received not by land/ forest owners, who are engaged in this pathway, but by the state that will account carbon sequestration and storage due to biomass yield increase after fertilization.

This means, EU subsidizes the more pollutive option – sewage sludge incineration over sewage sludge recycling in biomass plantations. Unfortunately, short rotation forestry cannot benefit from its huge CO_2 sequestration potential, as carbon sequestration is included in LULUCF calculations and benefits the state, which provides free emission allowances to real CO_2 polluters, but not those who sequestrate CO_2.

Even comparing to other waste incineration options, it can be observed how EU policy to grant cement producers with free emission allowances supports much higher CO_2 emissions. In Lithuania all dry sewage sludge, from all the cities (except Vilnius, where implementation of NutriBiomass4LIFE took place) has been transported for incineration without any phosphorus recovery at cement producer facilities in the North of Lithuania. This accounts over 1000 of heavy trucks annually going back and forward annually (up to 400 km per one way trip) and emission of huge volume of CO_2 from transportation. On the other hand, there are waste incineration plants which can incinerate sewage sludge locally without any or with minor emissions of CO_2 from transportation. But these waste incineration facilities do not receive free emission allowances as cement producer, therefore cannot compete for sewage sludge incineration locally with cement producer. This once more reveals, that in this particular case, EU climate policy evidently support the most CO_2 pollutive option.

11 Continuation

Replication and transfer of the NutriBiomass4LIFE sewages sludge recycling actions is heavily dependent upon policies and their implementation – whether incineration or circular economy prevails. During implementation of NutriBiomass4LIFE project economic conditions and policy priorities under massive investment into waste incineration facilities in Lithuania has changed, with a clear shift from circular to incineration economy. Today, in Lithuania, under lobby of waste incineration companies, sewage sludge incineration without nutrient recovery has a clear financial benefit because incineration of sewage sludge is indirectly subsidised by exemption of from CO_2 emission taxes and even direct grants of free emission allowance that can be sold at a good profit.

Taking into account current policy priorities for incineration of sewage sludge, it is difficult to expect that without policy changes NutriBiomass4LIFE project can be replicated and transferred at a large scale as it was expected at the start-up of the project.

Looking into future, NutriBiomass4LIFE CE model has good prospect to become very competitive over incineration (1) when EU Commission will set obligatory targets for member states for nutrient

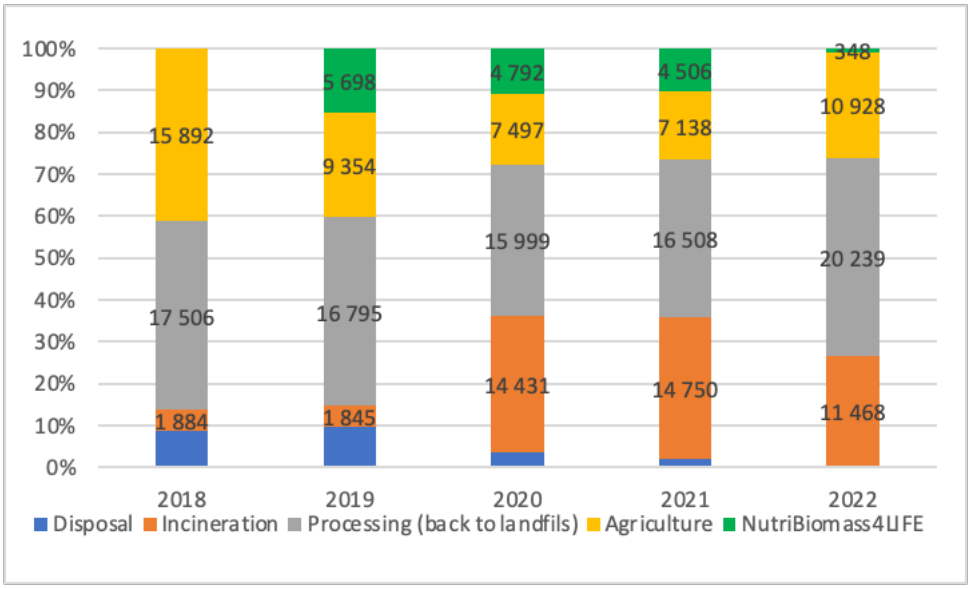
(nitrogen and phosphorus) recovery as defined in the new Urban Waste-Water Treatment directive adopted by the Council in October, 2023 and (2) when policies, direct and indirect subsidies will be weight against climate impact results, i.e. direct and indirect subsidies for more pollutive sewage sludge incineration without nutrient recovery will be stop and solid carbon removal through NutriBiomass4LIFE CCE model will rewarded (such possibility may emerge with the implementation of Carbon removal certification framework implementation).

11.1 Lithuanian market

Lithuanian municipal waste-water treatment plants produce appr. 40 thousand dmt of sewage sludge each year. Final sewage sludge management since start of the implementation of the project has significant changes. In 2019 NutriBiomass4LLIFE in biomass plantations reused 5,7 thousand dmt and that was about 15% of total Lithuania's sewage sludge. The next two years NutriBiomass4LLIFE sewage sludge share declined to 10% and in 2022 due to energy crisis and shift towards incineration declined to 1% (in 2023 Nutribiomass4LIFE share was 4%).

As it is seen from the Picture 11-1, the major changes occurred due to increase in incineration of sewage sludge after new waste incineration facilities started their operations. Dry sewage sludge digestate, which was primary target of Nutribiomass4LIFE project shifted towards incineration at Akmene cement production plant. In 2022 incineration of DMWTSD declined from 33% to 26% as due to global energy crises provoked by Russian invasion into Ukraine, extremely high natural gas prices and EU gas usage limitation policy, sewage sludge drying was stopped at some of waste water treatment plants. This led towards increase in share of "processed" and used in agriculture sewage sludge.

Picture 11-1. Changes in share of usage of sewage sludge in Lithuania (dmt)



The share of "processed" sludge still accounts about 35% of total sludge management – this sludge is typically goes to landfills under different category name – "reclamation of landfills", therefore officially not considered as landfilling. According to official records Lithuania is one of the leaders for composting in the EU, but the problem that this composting does not have anything with nutrient recovery and circular economy – simply it goes for landfilling. EU is considering revising categories of

waste management and everything that goes to landfills to be attributed to landfilling. Such changes would open additional possibilities for NutriBiomass4LIFE to reuse this sludge in biomass plantation fertilization, as currently under "gray" management practice there is about 1/3 of total country's sewage sludge.

NutriBiomass4LIFE established and mobilized biomass plantations that allows annually continuously to use 10-12 thousand dmt of DMWTSD in circular way - recently this part has been taken by more competitive incineration. In longer run, NutriBiomass4LIFE will be able to utilize its created potential to move DMWTSD towards nutrient recovery in circular way, but policy measures at the EU level to set obligatory targets for member states for nutrient (nitrogen and phosphorus) recovery as defined in the new Urban Waste-Water Treatment directive and removing sewage sludge incineration without nutrient recovery (i. e. co-incineration with other types of waste) from RED III list of resources for renewable energy production will be needed.

11.2 Replication

Recent policies supporting sewage sludge incineration does not provide sufficient economic background for replication of NutriBiomass4LIFE project with DMWTSD of VV.

All infrastructure (established and mobilized biomass plantations) related to ensure DMWTSD recycling in biomass plantations after completion of NutriBiomass4LIFE project will be present, therefore could be used by VV and other wastewater treatment plants for recycling of DMWTSD.

The major obstacle for VV in replication of the NutriBiomass4LIFE project nutrient rich sewage sludge recycling action (B2) is that DMWTSD incineration option comparing to replication option offered by NutriBiomass4LIFE model is financially more attractive. VV, being a public procurement subject, has to follow the cheapest waste management option unless that is otherwise defined by legislation:

- In case of DMWTSD usage in NutriBuiomass4LIFE project VV has to compensate transportation and spreading of DMWTSD costs in biomass plantations while Akmene cement plant offers to take DMWTSD at no cost to VV, which is less expensive option to VV. Because of existing EU policies waste incineration plants and especially cement producers have significant financial benefit incinerating DMWTSD. Under current favouring incineration policies, Akmene cement plant has very high profit margin from incineration to outcompete circular economy alternatives.
- DMWTSD usage for fertilization has certain operational disadvantage to VV comparing to incineration, as fertilization can be implemented during limited time period – from April 1 till November 15, therefore during winter DMWTSD has to be stored. While in case of sewage sludge incineration there are no limitations in incineration timing and that ensures constant outflow of DMWTSD from VV.

It is expected that NutriBiomass4LIFE project replication actions at VV to use DMWTSD in biomass plantation recycling in 2024 will be very limited but may improve significantly after expected policy changes in upcoming years.

11.3 Transfer

11.3.1 Transfer to other regions in Lithuania

Transfer of NutriBiomass4LIFE CE model to other large cities in Lithuania (Kaunas, Klaipėda, Šiauliai, Panevėžys, Alytus) is limited by the same incineration vs. circular economy policy considerations as in replication case, therefore without existing policies change it is not expected that other large cities' wastewater treatment plants will shift their policies of DMWTSD management from incineration toward fertilization of biomass plantations.

We started discussions to transfer NutriBiomass4LIFE CE model to smaller municipalities. NutriBiomass4LIFE CE model can be considered as ultimate integral part of MWTS management infrastructure, as all municipalities face constant pressure regarding their final MWTS management. Typically, smaller municipal wastewater treatment plants end their MWTS management in agriculture, but municipal companies face constant uncertainties as there is no longer term commitment from farmers and each year they have to look for new farmers and negotiate to use their MWTS. This is particularly sensitive issue in the regions with prevailing areas with natural constraints, where annual crop growing activities are not dominant and LAND 20-2005 requires immediate land ploughing after MWTS usage on agricultural land.

Some smaller municipal water supply and wastewater treatment companies expressed interested to establish local NutriBiomass4LIFE based models in cooperation with private landowners or even by investing themselves. E.g. average size 6-8 thousand population produce up to 100 dmt/year of MWTS (this is 24 regional canters in Lithuania). According to LAND 20-2005 requirements for MWTS usage in biomass plantation fertilization it is allowed to use 11 dmt/ha MWTS once in three years. For this purpose up-to 10 ha/year of biomass plantations are needed to use MWTS in circular economy way and total 30 ha of biomass plantations are needed to secure continues application of MWTS by rotating fertilized fields for each three years. The size of required land size is not significant but implementation of small scale NutriBiomass4LIFE would allow municipalities and their wastewater treatment plants to get out of constant headache related where to use sewage sludge.

The other important aspect to consider when establishing NutriBiomass4LIFE model for small municipalities are:

- Distance from wastewater treatment plant to biomass plantation fields – to have as short as possible (preferably up to 10-25 km), then transportation of WMTS can be done with smaller machinery and more transportation will be needed as typically dry matter content of such sludge is only 33%% comparing to 98% dryness of DMWTSD.
- Good access with roads, that would allow transportation machinery to go directly into the established biomass fields to spread MWTS.
- As most of the smaller municipal water treatment plants do not have anaerobic digestion and sludge drying facilities, it is required to establish biomass plantations at wider distances (5-6 m between rows) to allow to enter bigger machines into the fields and to plough between the lines of growing trees to insert MWTS into soil after application.
- As current biomass plantations are not suitable for smaller NutriBiomass4LIFE models, new biomass plantations have to be established at required distances between tree rows and that may open possibilities for higher carbon removals and benefitting from carbon markets.

Currently we are in the discussions with Moletai municipal water supply and wastewater treatment company to establish such NutriBiomass4LIFE model at the properties 150.1-150.2, the size of which is 44,5 ha and location is Molėtų r. sav., Suginčių sen., Saukiškių k. (23 km transportation distance from Moletai wastewater treatment plant). Total area needed for Moletai NutriBiomass4LIFE model is 30 ha. We are considering establishing this biomass plantation in spring 2024 and to start using MWTS of Moletai city WMTS in the second part of 2024 or starting 2025. This may be become circular economy demonstration model for municipal water supply and wastewater treatment companies of smaller cities.

Additionally, we are in discussions with medium size Taurage city municipal wastewater treatment plant, which produces DMWTSD and which is currently incinerated at Akmene cement production plant, and Taurage district heat supply company, which operates biomass boilers in Taurage city. NutriBiommass4LIFE model in Taurage city would involve 100 ha of biomass plantations establishment both for DMWTSD and biomass ashes usage for biomass plantations fertilization, and carbon removal actions. In 2024 we expect to develop Taurage NutriBiomass4LIFE project, and to start implementation from 2025.

11.3.2 Transfer to other EU countries

NutriBiomass4LIFE CE model transfer possibilities to other EU markets is quite limited due to technological and regulatory differences in each country.

First, technological differences in sludge management processes make significant impact on capabilities of application of sewage sludge in biomass plantations. Lithuania has advantage to use large part of countries sewage sludge in biomass plantation fertilization because about half of its sewage sludge is produced in the form of dry sewage sludge digestate (DMWTSD), which is easy to transport and spread in already growing biomass plantations. DMWTSD production is widespread in such countries like Germany, Netherlands, Austria but all of them have very limited direct sewage sludge application in agriculture and are moving into pathway for mono-incinerations with phosphorus recovery from ashes.

Other EU countries mainly (including our target countries Latvia, Sweden) do not have DMWTSD production therefore only dewatered sewage sludge or wet (appr. 33% dry mass content) sewage sludge digestate is available for fertilization purposes. The usage of high-water content sewage sludge digestate in biomass plantations is limited due to complicated spreading and ploughing requirements to insert sewage sludge in soil, which can be easily implemented in one year rotation agriculture, but not so easily in perennial crops or growing biomass plantations. Therefore, it is very complicated to use existing biomass plantations for wet sewage sludge spreading. In this case the establishment of new biomass plantations with higher distances between lines of trees is needed to ensure sewage sludge application between the lines without damage of tree roots when ploughing.

The establishment of new biomass plantations is very limited in many EU countries as regulation for that is different and it is less financially attractive option to farmers comparing to traditional agricultural activities. The situation may improve with implementation of Carbon Removal Certification Framework as longer rotation biomass plantations (trees on agricultural land), similar to forest establishment, have very huge potential for carbon removal and storage. If farmers and landowners

will be able to benefit from their climate actions, the attitude towards tree establishment on agricultural land may change and that may create background for NutriBiomass4lIFE model replication in other EU countries.

11.3.3 Transfer to Ukraine

Currently we investigate possibility to transfer NutriBiomass4LIFE CE model to Ukraine, which was recently accepted by the EU to start EU accession negotiations. Ukraine has a great potential for transfer and implement NutriBiomass4LIFE at a wide scale as Ukraine has land available for biomass plantation establishment and huge ned to shift from landfilling towards circular sewage sludge management.

The main part of sewage treatment facilities in Ukraine was designed and built in the 60s and 80s of the last century. These technologies are already outdated and do not comply with the European Directive 91/271/EEC "On urban wastewater treatment".

EU, World bank, EBRD, Japanese government and other multinational financial institutions stepped in to develop and support water supply and waste-water treatment reconstruction projects in the major cities of Ukraine. E.g. the municipality of Lviv has decided to build a new sludge treatment facility with biogas production, based on Cambi's thermal hydrolysis process followed by advanced anaerobic digestion and on 2020 awarded a consortium of Cambi (Norway) and Slovenian engineering company Riko with a contract to implement 31.5 million EUR reconstruction project. The project was targeting to convert sewage sludge digestate into exceptional quality and free of pathogens biosolids, making it suitable for land application. This project in Lviv (the population of 700 thousand) is very similar to that recontraction, developed with participation of CAMBI in Vilnius wastewater treatment plant, after that quality biosolids were available for NutriBiomass4LIFE project.

Unfortunately, Russian invasion in February 2022, put-on hold implementation water supply and waste-water treatment reconstruction projects in Ukraine. Water supply and waste-water treatment facilities has been under deliberate targeting of Russian missile and drone attacks, to destroy vital infrastructure in Ukraine, therefore during the war the major task is to ensure water supply to population and at least minimal waste-water treatment at the facilities.

The soviet design of wastewater treatment facilities in Ukraine typically do not include the final stage of sewage sludge management. The use of sewage sludge in agriculture is a recommendation, but so far in Ukraine the most common method of waste management is placing sewage sludge in holding ponds or landfills. Facilities for such a disposal of sewage sludge are sources of environmental pollution and require large territories. Today in Ukraine, only 3-5% of sewage sludge is used in agriculture, one of the reasons, that sewage sludge is still highly polluted with heavy metals, from outdated soviet heavy industry facilities.

Pursuant to the requirements of the fifth paragraph of Article 11 of the Law of Ukraine "On Drinking Water, Drinking Water Supply and Drainage", the MCTD order dated 12.12.2018 No. 341 "Procedure for the reuse of treated wastewater and sludge if the norms of maximum permissible concentrations of pollutants" was adopted. According to order No. 341, sewage sludge that has undergone the necessary technological stages of treatment can be used for soil fertilization in accordance with the Law of Ukraine "On Land Protection" taking into account the features defined by Article 39 of the said

Law and as an alternative type of fuel in accordance with the Law of Ukraine "On Alternative Energy Sources". Sewage sludge used for fertilization must meet the quality requirements of DSTU 7369:2013 "Sewage. Requirements for Sewage and Sludge for Irrigation and Fertilization" and have a positive conclusion of the state sanitary-epidemiological examination.

According to DSTU 7369: 2013 "Sewage. Requirements for Sewage and Sludge for Irrigation and Fertilization" sewage sludge is divided into five groups according to heavy metal concentrations in sewage sludge as presented in Table 11-1. The quality of sewage sludge, attributed to groups 1-4, is compatible to SSD quality requirements.

Table 11-1. Comparison of heavy metal limits (mg/kg) in sewage sludge for usage in agriculture according to Ukrainian DSTU 7369: 2013 and EU SSD requirements

Heavy metal limits (mg/kg)	Group 1	Group 2	Group 3	Group 4	Group 5	SSD
	Using (or composting) in rates adequate to standard fertilizers	Using 3-4 dmt/ha annually or up to 10 dmt/ha once in three years	Using 5-6 dmt/ha once in 5-7 years with mandatory soil monitoring	For compost production only, not for direct agricultural use	Not allowed to use in agriculture, can be used in greenery, forestry	
Strontium (Sr)	50-70	75-100	100-300	300-500	400-500	
Lead (Pb)	100-200	400-600	600-750	750-1200	1200-1500	750-1200
Mercury (Hg)	2-5	*5-10*	10-15	15-20	20-30	16-25
Cadmium (Cd)	3-5	*5-15*	15-30	30-40	30-40	20-40
Nickel (Ni)	50-75	*75-150*	150-200	200-400	400-600	300-400
Chrome (Cr)	100-400	*400-600*	600-750	750-2000	2000-4000	
Manganese (Mn)	250-750	*750-1500*	1500-2000	2000-3000	3000-6000	
Zinc (Zn)	300-1000	*1000-2000*	2000-2500	2500-4000	4000-7000	2500-4000
Copper (Cu)	100-300	*300-700*	700-1500	1500-2500	2500-4000	1000-1750
Cobalt (Co)	5-20	20-50	50-100	100-150	150-200	

High quality water supply and wastewater treatment are essential benefits offered the EU to its citizens, therefore during accession period, Ukraine will have to make massive investments into modernization of water supply and wastewater treatment facilities (mainly funded by EU through Green recovery of Ukraine programs) to comply to EU regulation. This will open pathways to use sewage sludge in circular economy way and transfer of NutriBiomass4LIFE model, as there will be a strong need to shift from landfilling towards reuse on land or nutrient recovery.

NutriBiomass4LIFE project transfer may offer the following key benefits to Ukraine's green recovery:

- To contribute to Ukraine's afforestation targets, as during the war thousands of ha of forests have been destroyed.
- To contribute towards Ukraine's shift towards green circular economy.
- To contribute to Ukraine's transition from fossil towards renewable energy, as heating sector will have to shift towards biomass-based energy – Nutribiomass4LIFE model will be able to secure significant volumes of biomass for energy through cascading use of biomass.
- To contribute towards Ukraine's transition towards climate neutrality – the establishment of new biomass plantations, shift of sewage sludge management practices from landfilling towards circular economy and energy transition may remove and store millions of tons CO_2.

We consider the following pathways for Nutribiomass4LIFE CE model transfer to Ukraine:

- We started discussion with Ukrainians authorities, municipalities, and local actors (farmers) regarding transfer of the NutriBiomass4LIFE model to Ukraine.
- We consider starting NutriBiomass4LIF CE model transfer from western part of Ukraine (Lviv, Rivne, Volyn regions), the area which is less agriculture intensive and more unused land available for NutriBiomass4LIFE plantations establishment.
- We see that NutriBiomass4LIFE model in Ukraine may have to be expanded by upstream integration into reconstruction of wastewater treatment and sewage sludge processing through anaerobic digestion to supplement these investments to ensure final steps for circular sewage sludge management.
- We are analysing possibilities to secure land for NutriBiomass4LIFE plantation establishment – current legislation allows to lease land from municipalities for up to 50-year term. We are looking towards possibilities to start the project from establishment of NutriBiomass4LIFE plantation in 2025/2026 and in several years to move towards stable 1000-3000 ha of biomass plantations establishment each year.
- We are looking for possibilities to secure hybrid poplar seedling supplies as from 1 million to 5 million of new trees will have to be planted annually to meet biomass plantation establishment targets.
- We are strongly looking at carbon markets developments and Carbon Removal Certification Framework implementation as transfer of NutriBiomass4LIFE model in Ukraine will lead towards removal of millions of tons of CO_2 and carbon markets may become a primary source of funding for the NutriBiomass4LIFE CE model transfer to Ukraine.

Conclusions

The key lessons we learned from nutrient from sewage sludge recycling in biomass plantations during implementation of NutriBiomass4LIFE project:

- Over 4 years of implementation of the project 16500 dmt of dry sewage sludge digestate were recycled in NutriBiomass4LIFE biomass plantations. NutriBiomass4LIFE project target (27000 t) was implemented by 61% because of VV inability to supply dry sewage sludge digestate for recycling in NutriBiomass4LIFE CCE model. The key reason why VV was not able to supply dry sewage sludge digestate for the recycling were (1) constant technical faults at VV sewage sludge drying facilities, (2) decrease in sewage sludge output at VV, (3) stoppages in sewage sludge digestate drying operations (2022) due to energy crisis provoked by Russian invasion into Ukraine and (4) shift towards incineration of sludge due to heavy subsidies.
- The quality of dried sewage sludge digestate in Lithuania proved to be sufficient to ensure sewage sludge usage in circular way – have rich concentrations of nitrogen (N) which is of primary importance for plant growth on nitrogen deficient soils, where biomass plantations are primary established, phosphorus (P), and organic carbon, which is very important for soil health improvement to restore humus content. During implementation of NutriBiomass4LIFE project 795 t of total nitrogen (N), 361 of total phosphorus (P), 55 t of total potassium (K) and 3935 t of organic carbon were recycled in 937 ha of biomass plantations.
- The risk of contamination of sewage sludge, used in NutriBiomass4LIFE project, was not high as concentrations of heavy metals, except for zinc (Zn) and some fluctuations in some other

metals, were meeting requirements for fertilizing materials. The analysis shows, that while fertilizing with dried sewage sludge digestate the risk for contamination with parasites and organic contaminants (PCB and PAH) is low. Soil and water monitoring does not show any increased risks of soil and water contamination due to fertilization with sewage sludge.

- It is estimated that overall costs for recycling of dry sewage sludge digestate in biomass fields total 33 eur /t dry sewage sludge digestate. Financial calculations show that revenues from biomass yield increase due fertilization may outweigh initial (fertilization) costs, but because of very significant time span between initial investment outflow and revenue inflow for biomass harvesting, full or partial compensation of dry sewage sludge digestate recycling costs is needed to make CE model economically attractive to farmers and landowners.
- Implementation of NutriBiomass4LLIFE project action (B2) "Recycling of nutrients from municipal water treatment sludge" had significant negative carbon footprint, which totalled to minus 22469,7 tCO_2. The major inputs towards negative carbon footprint was from (1) soil organic carbon increase because of application of dry sewage sludge digestate, (2) biomass yield increase because of fertilization and (3) nutrient replacement effect.
- Through the adoption of European Green Deal, NutriBiomass4LIFE CE model is coherent with multiple EU and national policies and legal regulations. Nevertheless, we encountered some incoherencies among several policies in particular what relates to prioritising usage of sewage sludge in circular way (circular economy policy) over incineration (energy policy).
- Replication and transfer of NutriBiomass4LLIFE project in short run will be limited to existing unfavourable policies, which give strong priority towards incineration of sewage sludge over nutrient recovery.
- NutriBiomass4LIFE CE model has good prospect for replication and transfer by becoming very competitive over incineration under the following policy changes (1) when EU Commission will set obligatory targets for member states for nutrient (nitrogen and phosphorus) recovery as defined in the new Urban Waste-Water Treatment directive adopted by the Council in October, 2023 and (2) when policies, direct and indirect subsidies will be weight against climate impact results, i.e. after removing sewage sludge incineration without nutrient recovery (i. e. co-incineration with other types of waste) from RED III list of resources for renewable energy production.