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Generation of Solid Recovered Fuel from Sewage Sludge Compost

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The paper presents results of the research which was carried out in KTU APINI when implementing one stage of the PF7 program project “Polygeneration of energy, fuels, and fertilizers from biomass residues and sewage sludge (ENERCOM)” (No TREN/FP7/EN/218916). The research objective was to assess possibilities of producing solid recovered fuel (SRF) from compost produced from pre-treated sewage sludge and biomass residuals in “Soil-Concept” plant (Luxemburg). Feasibility of producing pellets and briquettes using the composites of compost, sawdust, and peat was analyzed. Technical and environmental evaluations of SRF production were carried out on the basis of pelleting and briquetting tests. Main chemical and physical parameters of produced SRF were analyzed and compared to the recovered fuel classificatory (CEN/TC 343). All pellets and briquettes, produced during the experiment, were attributed to a certain class of recovered fuel.

Results of technical and environmental evaluations of SRF production and their burning as well as conclusions and recommendations made are presented.

Key words: *Solid recovered fuel, sewage sludge, compost, sawdust, peat, pellets, briquettes, environmental impact assessment.*

1. Introduction

Energy production from renewable energy sources (RES) is one of the major goals of the EU energy policy defined in the White Paper “Energy for the future: renewable energy sources”. All the EU member states, aware of the problems of climate change, are obligated to achieve certain rates of RES consumption in the EU up to 2020. These rates depend on the already used RES content and other conditions. Lithuania is obligated to achieve at least 23% of final energy consumption from RER up to 2020.

According to the data of the Statistics Lithuania, 18.3 % of the total energy consumption (approx. 15.6 % of final energy consumption) was produced from RES in Lithuania in 2011 [Fuel and energy balance 2011]. There are lots of promotional mechanisms for the projects of RES to be implemented in Lithuania. Many efforts have been taken for maximum use of biomass and wind energy. The following purposes are scheduled in the RES promotion action plan for 2010-2020: to increase both wind power capacity from 52 MW (2009 m.) to 400 MW (2020 m.) and biomass power capacity from 29.5 MW (2009 m.) to 124 MW [LITBIOMA 2008]. During the period of 2009-2011, wind power capacity increased up to 178 MW, and biomass power capacity - up to 45 MW [Fuel and energy balance 2011]. It is expected to employ energy potential from solid municipal waste such as landfill biogas, separating biodegradable fractions from solid municipal waste, and extracting biogas from fermentation process.

Biogas recovery from a waste water treatment plant by means of anaerobic processing of sewage sludge is one of widely applied possibilities of RER in Lithuania. Extracted biogas is used in cogeneration plants for energy production. Produced energy is used for farther sewage sludge treatment.

Such anaerobic sewage sludge treatment plants have been successfully operating in other EU countries for over 10 years. Currently, these plants’ optimization projects are implemented.

The volume of sewage sludge after anaerobic treatment could increase. The question for today in Lithuania is what to do with digested sewage sludge. Some of the waste water treatment plants analyze the possibilities to produce solid recovered fuel (SRF) from dried sewage sludge.

Unfortunately, the net calorific value of digested sewage sludge is lower than that of primary sludge [Wetle and Wilk 2010, Houdkova et al. 2008]:

- primary sludge: 13.30– 17.50 MJ/kg (in dry matter);
- sludge after fermentation: 6.7–12.0 MJ/kg (in dry matter).

Moreover, a lot of additional energy is used for sludge drying.

It is suggested to utilize the sewage sludge by mixing it together with other properly selected wastes, i.e. with under-grade sized coal, with waste from animal waste utilization plants, and with wood waste [Wrozek 2012]. These components can be mixed and pressed according to the requirements for SRF production. In this case, the net calorific volume of produced SRF is increased up to 15-19 MJ/kg. For example, the net calorific value of SRF from 80% of sewage sludge, 19% of sawdust, and 1% of burnt lime is 15.54 MJ/kg (in dry matter) or 13.23 MJ/kg, when moisture content is 10.37%. [Malgorzata Wrozek 2012].

In many countries digested sewage sludge after anaerobic treatment is used for the compost production. Different composting technologies are developed for the purpose of optimizing the composting process and reducing the environmental impact. Sewage sludge is mixed with biomass residuals for improving the process and the quality of produced compost.

During 2008-2012, the Institute of Environmental Engineering of Kaunas University of Technology (KTU APINI) participated in the PF7 program “Energy” project “Polygeneration of energy, fuels and fertilisers from biomass residues and sewage sludge (ENERCOM)”. Project coordinator: Ifas - Institute for Applied Material Flow Management (Germany). Project partners: Soil-Concept S.A. (Luxembourg), LEE (Luxembourg), Bisanz Anlagenbau GmbH (Germany), BIOS Bioenergiesysteme GmbH (Austria), KTU APINI (Lithuania), Kuhbier Law Firm (KLF) (Belgium), B.A.U.M. Consult GmbH (Germany).

The aim of the project was to demonstrate high-efficient polygeneration of electricity, heat, solid fuels, and high-value compost/ fertilizers from sewage sludge and greenery waste mixed with biomass residues. The project concept allows achieving high overall energy efficiency by

(1) mixing sewage sludge with greenery waste and biomass residues, and using low-temperature environmental heat, and heat from the composting process for drying sewage sludge;

(2) highly efficient gasification process;

(3) saving transport energy due to a better overall material flow management inherent to the concept [ENERCOM].

The compost production company, owned and operated by the consortium partner Soil-Concept in Luxemburg, was chosen as pilot company. Aerobic treatment with forced air supply methods is used for compost production from sewage sludge, greenery waste, and biomass residues.

Main steps of polygeneration process [ENERCOM] are:

- The input materials of this process: stabilize sewage sludge with 25-30% of dry substance (DS) content, municipal green waste (grass, branches, etc.) with 40-50% of DS, and bark with 60% of DS;
- These input materials are pre-composted (mixed and dried in concrete silos, i.e. biological drying), thus, they increase DS up to 60-65%.About 10% of pre-composted materials will be further processed to high quality compost;
- Other part of prepared compound will be supplied through the first stage of poly-compost-gasification (PCG) process - thermal drying (up to 85-90% of DS content);
- Heat energy for thermal drying is produced in two heat recovery units and CHP (combined heat and power) exhaust gas.
- Second stage of PCG is fluidized bad gasifier. Produced gas is cleaned. The ash is separated, and investigated as a component for compost production (after removal of heavy metals);
- Part of dried compound (about 70%) is a potential material for SRF production in pellet and/or briquette form.

One of the goals of the ENERCOM project is to assess the possibilities of producing SRF from the above mentioned pre-composted material (further–compost).

Technical and environmental possibilities to produce SRF from various compositions of raw materials (compost, compost and sawdust, compost and peat, compost, sawdust and peat) in pellets and briquettes were analyzed by KTU APINI researchers with technical assistance of several Lithuanian companies and ENERCOM project partners during 2009-2010. First results of that research are presented below.

In parallel, BIOS carried out circumstantial chemical analysis of raw materials for compost production, because sewage sludge is used from different sources and of different compositions with greenery waste and biomass residues. Pre-composting time, compost different fractions, and its chemical characteristics were analyzed [BIOS 2009].

2. Methodology of SRF production analysis

The algorithm for evaluation of technical and environmental possibilities to produce SRF from the compost used for research is presented in Figure 1.

The objective of the first (I) stage was to carry out pelleting and briquetting tests with specially prepared compost from the Soil-Concept plant and additional materials (sawdust, peat). Technical aspects of pelleting and briquetting processes were evaluated. Main steps to implement the objective were taken:

- Possibilities of pellets and briquettes formation from compost and various compounds of compost, sawdust and peat were evaluated: pelleting tests were carried out in the pellets production company with technical assistance from Logitrita Ltd.; briquetting tests were carried out in the briquettes production company Medinukai Ltd. with company's technical assistance;
- Pellets and briquettes were successfully produced from 14 various compounds of compost, sawdust, and peat;
- Materials and energy balances of all technological processes were formed for the purpose of evaluating relative environmental indicators - quantity of one of the input or output flows of technological process (e.g. raw material, energy, waste, air emissions, etc expressed by unit per year) for producing one ton of manufactured product;
- In order to develop material and energy balance for each successful test, the Excel database was developed, containing input and output flows for each technological process. This database was used for the evaluation of the environmental impact assessment (EIA) during recovered fuel production and burning;
- Results of the above mentioned analysis were used for the environmental impact assessment (EIA) of pellets and briquettes production.

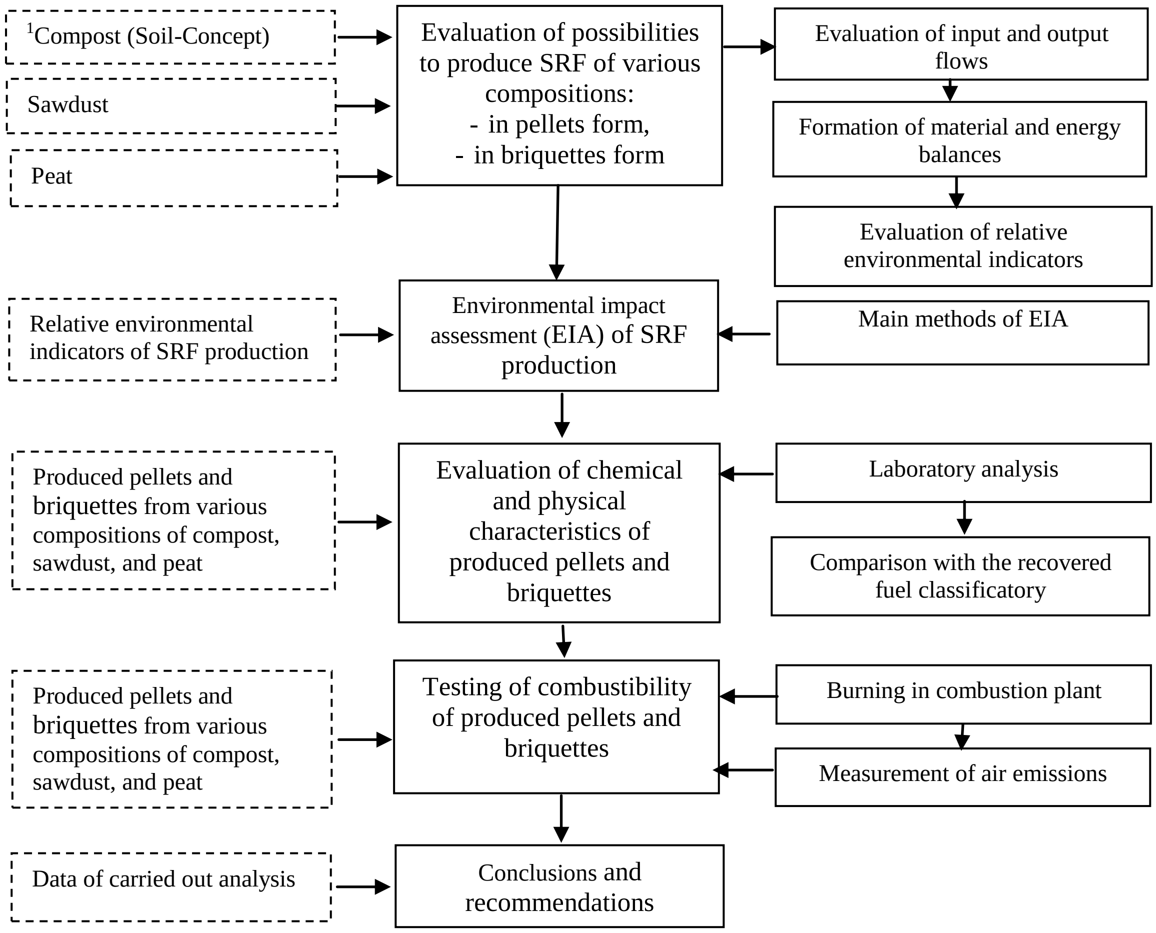


Fig. 1. SRF production from compost following the research methodology
[1]Compost - pre-composted materials: stabilized sewage sludge (about 50%), municipal green waste (about 26%), and other biomass residuals (mixing and biological drying during approx. 3 weeks)

The objective of the second (II) stage was to analyze main quality characteristics of pellets and briquettes produced from various compositions from compost, sawdust, and peat. The following main steps to implement the objective were taken:

- Determination of main chemical and physical characteristics (laboratory analysis) was carried out in the laboratory of Agrochemical Research in the Center of Lithuanian Agrarian and Forest Science;
- Data evaluation and comparison with the recovered fuel classificatory CEN/TC 343 [European Committee for Standardization 15508:2006].

The objective of the third (III) stage was to evaluate burning possibilities of produced SRF. The following main steps to implement the objective were taken:

- Testing of combustibility of produced SRF;
- Evaluation of main air emissions during SRF burning (dust, CO, NOx, SO_2).The Ekopaslauga Ltd., which has the license to evaluate the emissions from stationary pollution sources, i.e. from the fuel combustion plant, made measurements of air emissions.

The analysis results are presented and discussed in the paper.

3. Results of technical evaluation of SRF production

As mentioned above, pelleting tests were carried out in the pellets production plant. Technical conditions of pelleting tests:

- Capacity of granulator and entire technological line – 1 t/h (50% of load);
- Main equipment of technological line: transporter, mill, cyclone, collecting bin, stirrer, press, cooler, packing and weighing-machine;
- Matrix form – cylindrical (8 mm);
- Press (pelleting equipment) with installed electrical power – 90 kW; electrical power of all technological line – 131.40 kW;
- Raw material consumption – 20 kg for each experiment.

Input (raw) materials:

- Compost was delivered from the Soil-Concept S.A., Luxembourg (moisture content – 12%);
- Sawdust: 30% of deciduous trees sawdust and 70% of softwood (before palletizing dried to 11% of moisture content);
- Peat: black crumbled peat (before palletizing dried to 12% of moisture content).

Importantly, compost was not screened before using it for the experimental SRF production in Lithuania.

Pellets production process proceeded successfully from a technological point of view. Good quality pellets were produced from all intended compositions:

- 100% of compost;
- Compost-sawdust (C/S):
- 10% of compost, 90% of sawdust (C/S 10/90);
- 20% of compost, 80% of sawdust (C/S 20/80);
- 40% of compost, 60% of sawdust (C/S 40/60);
- 50% of compost, 50% of sawdust (C/S 50/50).
- Compost-peat (C/P):
- 30% of compost, 70% of peat (C/P 30/70);
- 50% of compost, 50% of peat (C/P 50/50);
- 70% of compost, 30% of peat (C/P 70/30).

Material and energy balance was formed for each pellets production test. Extract from the created database is presented in Figure 2 with an example of material and energy balance of one of the pellets production processes and evaluation of relative environmental indicators.

Manufactured products demonstrate good mechanical strength (toughness). During pelletizing of compost containing sawdust, it has been estimated that to increase the compost content in the compound, the pelletizing time in stirrer and press is prolonged resulting in an electricity consumption increase from 0.22 kWh/kg of manufactured production to 0.38 kWh/kg. During pellets production from compost containing peat, the operational time decreases considerably and it has an influence on a decrease in electricity consumption (to 0.143 kWh/kg).

When choosing the matrix, it is considered that the length (h) of the matrix‘s cavities should be about 7-8 times higher than its diameter (d), but not less than 6.5 times. In this way, the pellet is formed better. In our case, when the diameter of the matrix‘s cavities is 8 mm, cavity length (h) was between 52 to 64 mm.

Depreciation of the matrix is characterized by an increase in cavities‘ diameters. Meanwhile, the cavities‘ length remains unchanged and such a matrix can not handle the formation of a pellet from raw material. Usually, when pelleting high quality sawdust, one matrix is sufficient to produce 1000 tons of pellets. When the content of the compost in pellets increases to 50%, the lifetime of the matrix may decrease (up to 500 tons of pellets produced). In most cases this occurs due to sand particles in the composition of the compost.

The balance of pellets production material and energy shows that the loss of material is up to 5%. The biggest part of this loss is caught in cyclone and goes back to production line. Thus, the real material loss (solid part) is up to 0.2%.

Briquetting tests were carried out in the briquettes production plant. Technical conditions of tests:

- Main equipment of the technological line: transporter, automatic stirrer for mixing compounds, cyclone, raw materials supply pipe, briquetting press, packing equipment;
- Efficiency – 0.4 t/h;
- Installed electrical capacity of stirrer: 18.5 kW;
- Installed electrical capacity press – 30 kW;
- Automatic setting of the matrix:
    - Horizontal pressure – 200 bar;
    - Vertical pressure was changed depending on the used raw materials:
        - for sawdust – 100 bar;
        - for sawdust and compost – 70 bar, when the compost content in a sample increases – 60 bar;
        - for compost, peat, and sawdust mixture – 65 bar;
        - for compost and peat – 50 bar.
- Packing using polythene packing material was done manually.

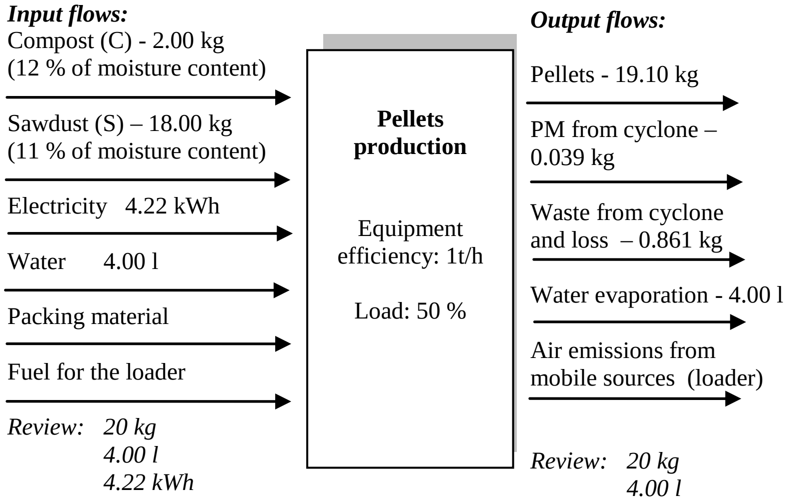
Input (raw) materials:

- Compost was delivered from the Soil-Concept S.A., Luxembourg (moisture content – 12%);

- Sawdust: 30% of deciduous trees sawdust and 70% of softwood (before palletizing dried to 11% of moisture content);
- Peat: black crumbled peat (before palletizing dried to the 12 % of moisture content).

From a technological point of view, the briquettes production process proceeded successfully. Good quality briquettes were produced from all intended compositions:

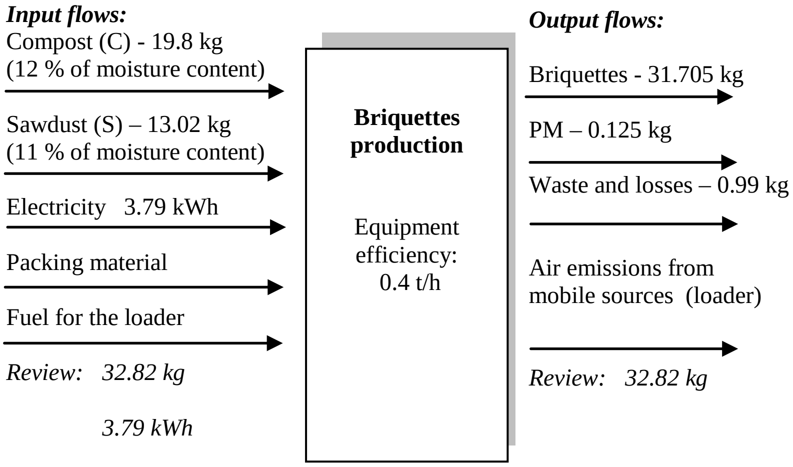
- Compost-sawdust :
  - 60% of compost, 40% of sawdust (C/S 60/40);
  - 78% of compost, 22% of sawdust (C/S 78/22);
  - 89% of compost,11% of sawdust (C/S 89/11);
- Compost-peat:
  - 25% of compost, 75% of peat (C/P 25/75);
  - 44% of compost, 56% of peat (C/P 44/56);
  - 65% of compost, 35% of peat (C/P 65/35);
- Compost-sawdust-peat:
  - 40% of compost, 50% of sawdust, and 10% of peat (C/S/P 40/50/10).



Input and output flows	Relative environmental indicators	
	units/kg of RM	units/kg of MP
Raw materials, kg C (12% moisture) S (11% moisture)	1 C: 0.1 S: 0.9	1.047 C: 0.105 S: 0.942
PM, g	1.95	2.04
Waste from cyclone and loss, g	43.05	45.08
Electricity, kWh	0.211	0.221
Water, l	0.200	0.209

RM – raw materials;
MP – manufactured product;
PM – particulate matter (air emissions)

Fig.2. Material and energy balance and environmental indicators of pellets production from 10% of compost, 90% of sawdust (C/S 10/90) (Extract from the created database)



Input and output flows	Relative environmental indicators	
	units/kg of RM	units/kg of MP
Raw materials, kg C (12% moisture) S (11% moisture)	1 C: 0.603 S: 0.397	1.036 C: 0.625 S: 0.411
PM, g	3.81	3.94
Waste from cyclone and loss, g	30.16	31.23
Electricity, kWh	0.115	0.120

RM – raw materials;
MP – manufactured product;
PM – particulate matter (air emissions)

Fig.3. Material and energy balance and environmental indicators of briquettes production from 60% of compost, 40% of sawdust (C/S 60/40) (Extract from the created database)

Material and energy balance was formed for each briquettes production test. Extract from the created database with an example of material and energy balance of one of the briquettes production process and evaluation of relative environmental indicators is presented in Figure 3.

During briquetting of compost containing sawdust, it was estimated that in case of an increase in compost content in the compound, the briquetting time reduces, and electricity consumption decreases from 0.12 kWh/kg of manufactured production to 0.106 kWh/kg.

During briquettes production from compost containing peat, in case of an increase in compost content in the compound, the operational time decreases considerably; it has an influence on a decrease in electricity consumption (to 0.068 kWh/kg).

Briquettes of C/S/P 40/50/10 mixture were produced successfully, the quality of briquettes was high and electricity consumption was 0.09 kWh/kg of manufactured production.

The briquettes production material and energy balance shows that the loss of material is up to

10%. The biggest part of this loss is caught in cyclone and goes back to the production line. Thus, the real material loss is up to 0.2%

4. Results of environmental impact assessment (EIA) during SRF production

The heat demand for drying raw material, for example, sawdust from 50-55% to approx. 10-15% during wood pellet production is 1,200 kWh/t of evaporated water [Thek and Obernberger 2009].

During EIA experiments, the environmental impact of raw material preparation was not analyzed, because of new innovative methods for sewage sludge drying, inc. the use of low-temperature environmental heat, whereas heat from the composting process was further investigated by other project partners [ENERCOM]. Therefore, the assumption has been accepted that received raw materials (compost, sawdust, peat) are already dried to the required moisture (as in the case of our analysis in Lithuania): for briquetting the required maximum moisture – 12 %, for pelleting – up to 15 %.

Relative environmental indicators were evaluated analyzing the material and energy balances of performed briquetting and pelleting processes (see Figs 2, 3).

Using the net calorific value and Excel database, the amount of the fuel, necessary to produce 100 MWh of heat energy, is evaluated. Further, using the environmental indicators, the impact on the environment during the SRF production processes of the particular amount of the fuel is assessed. The results are presented in Tables 1 and 2.

Table 1. Comparison table: EIA of production of SRF made of compost and sawdust (amount of recovered fuel ≡100 MWh)

SRF composition		C/S 10/90	C/S 20/80	C/S 40/60	C/S 50/50	C/S 60/40	C/S 78/22	C/S 89/11	C 100
	Units	*pellets*	*pellets*	*pellets*	*pellets*	*briquettes*	*briquettes*	*briquettes*	*pellets*
Net calorific value	MWh/t	3.67	3.44	3.14	2.96	2.72	2.40	2.01	1.06
Moisture content	%	17.31	17.04	16.36	16.62	11	10.66	9.65	29.19
SRF volume for the production of 100 MWh	t	27.29	29.07	31.83	33.75	36.73	41.60	49.85	94.69
Compost consumption	t	2.86	6.12	13.40	17.85	22.94	34.15	46,81	101.16
Sawdust consumption	t	25.71	24.48	20.10	17.85	15.09	9.62	5.65	0.00
Water consumption	m^3	5.71	6.12	8.38	8.93	0.00	0.00	0.00	25.29
Electricity consumption	MWh	6.02	7.62	10.87	12.96	4.39	4.66	5.29	11.22
Air emissions	kg	55.55	79.32	73.40	81.50	144.47	183.99	233.94	277.05
Matrix consumption	unit	0.03	0.04	0.06	0.11	0.01	0.03	0.03	0.32
Waste volume	t	1.23	1.45	1.60	1.88	1.15	1.99	2.38	6.20

Table 2. Comparison table: EIA of production of SRF made of compost and peat (amount of recovered fuel ≡100 MWh)

SRF composition		C/P 25/75	C/P 44/56	C/P 30/70	C/P 50/50	C/P 70/30	C/P/S 40/50/10
	Units	*briquettes*	*briquettes*	*pellets*	*pellets*	*pellets*	*briquettes*
Net calorific value of recovered fuel	MWh/t	3.53	2.96	1.55	1.35	1.21	3.33
Moisture of recovered fuel	%	16.09	14.39	25.09	24.11	30.56	14.69
SRF volume for the receiving of 100 MWh	t	28.31	33.78	64.60	73.83	82.53	29.99
Compost consumption	t	7.99	15.72	20.31	38.74	60.81	12.34
Sawdust and peat consumption	t	23.53	19.84	47.40	38.74	26.06	19.06
Water consumption	m^3	0.00	0.00	16.93	19.37	21.72	0.00
Electricity consumption	MWh	2.17	2.28	17.02	13.52	11.82	2.80
Air emissions	kg	59.06	79.14	152.56	185.30	219.84	75.61
Matrix consumption	unit	0.01	0.01	0.22	0.25	0.28	0.01
Waste volume	t	3.15	1.70	2.96	3.46	4.12	1.34

Conclusions concerning the SRF production from compost (12 % of moisture content) and sawdust (up to 11 % of moisture content) in the form of pellets (see Table 1) are as follows:

- If the compost content in SRF increases from 10 to 50%, the net calorific value decreases by 19%, therefore the volume of required fuel increases approx. by 23.67 %, though the consumption of sawdust decreases;
- If the compost content in SRF increases (from 10 to 50%), electricity consumption increases more than twofold (from 6.02 MWh to 12.96

MWh). It is related to the prolongation of the pellets production time: the bigger compost volume in pellets composition, the longer and more difficult the pelleting process;

- Furthermore, a bigger compost volume in the pellets composition determines bigger emissions of solid particles (C) (air emissions increased by 47%) and greater waste generation (waste volume increased by 54%);
- Production of SRF (in pellets form) from compost and sawdust with the maximum compost content of 20% causes the minimum environmental impact.

Conclusions concerning the SRF production from compost (12% of moisture content) and sawdust (up to 10% of moisture content) in the form of briquettes (see Table 1) are as follows:

- If the compost content increases, calorific value of SRF decreases, and the volume of recovered fuel required to produce the same amount of heat energy (e.g. 100 MWh) also increases (the same situation as in the pellets production);
- If the compost content increases (from 60 to 89%.), consumption of electrical energy increases by 20.5%, but still it remains lower compared to the pellets production process;
- If the compost content increases (from 60 to 89%), the volume of PM emissions increases also (by 61.9 %). It is related to the usable emission factor: PM emissions during dry sawdust feed to the mill are 0.097 g/s, compost feed to the mill is 0.290 g/s. In this case, if the compost content increases, air emissions also increase. The situation concerning raw materials milling is the same: PM emissions during sawdust milling are 0.169 g/s, during compost milling – 0.230 g/s. Consequently, it is suggested in the future to use the maximum closed type system (the raw materials' feed to the mill, raw materials' milling);
- The SRF production in briquettes form from compost and sawdust with the maximum compost content of 60% causes the minimum environmental impact.

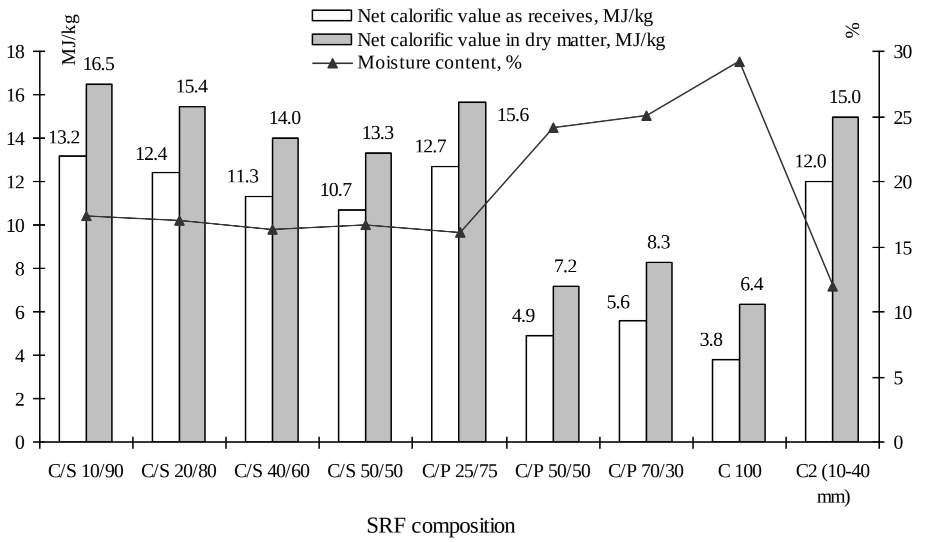


Fig. 4. Correlation between composition of SRF, its net calorific value (MJ/kg) and moisture content (%)

Conclusions concerning SRF production from compost and peat (see Table 2) are as follows:

- Different types of peat were used for briquettes and pellets production. The moisture of pellets is higher than in briquettes; therefore, the caloricity of pellets is lower than that of briquettes;
- If the compost volume increases, the net calorific value (as received) decreases;
- As observed during the SRF production process from compost and sawdust, the largest amount of electricity was consumed in pellets production;
- From an environmental point of view, the minimum impact is made on the environment, when there is a minimum content of the compost in the composite;
- The minimum impact on the environment is made during the SRF production from the compost and peat in the form of briquettes when the content of compost in the composite does
- not exceed 25%, and 30% when producing SRF in pellets form;
- Competent results were obtained during the production of the composite from 3 compounds (C/P/S 40/50/10) in the briquettes form.

5. Chemical and physical characteristics of produced SRF

For the purpose of determining physical and chemical characteristics of produced briquettes and pellets from different compositions, the laboratory analysis was carried out in the Laboratory of

Agrochemical Research of the Lithuanian Agrarian and Forestry Research Center.

The following characteristics of SRF were determined: moisture content (%), net calorific values as received and in dry matter (MJ/kg), ash content in dry matter (%), sulfur (S), nitrogen (N), carbon (C), chlorine (Cl) content in dry matter (%); cadmium (Cd), copper (Cu), lead (Pb), nickel (Ni), manganese (Mn), iron (Fe), chromium (Cr), zinc (Zn), arsenic (As), mercury (Hg), calcium (Ca), magnesium (Mg), natrium (Na), kalium (K), aluminium (Al) contents in dry matter (%).

Part of the results of the laboratory analyses of pellets and briquettes from various compositions of compost (without screening), sawdust, and peat are presented in Figures 4-9.

There is obvious correlation between the net calorific value as received, C, and moisture content (see Figs 4, 5). In case of increasing moisture content, net calorific value decreases. The net calorific value increases proportionally to an increase in C content in SRF. Carbon content in dry matter of compost amounts only to 22%, in compost 10-40 mm fraction – more than 36% (see Fig.5).

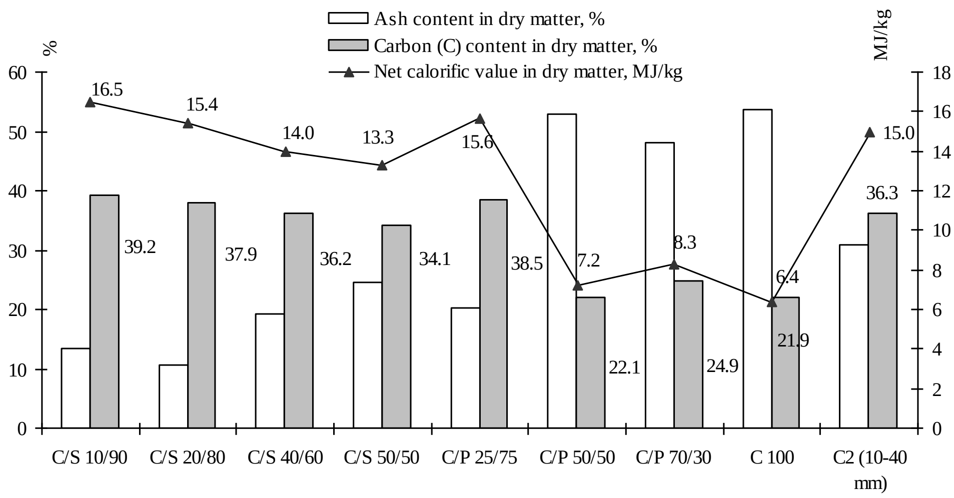


Fig. 5. Correlation between SRF net calorific value (MJ/kg) and its carbon (C) and ash content in dry matter (%)

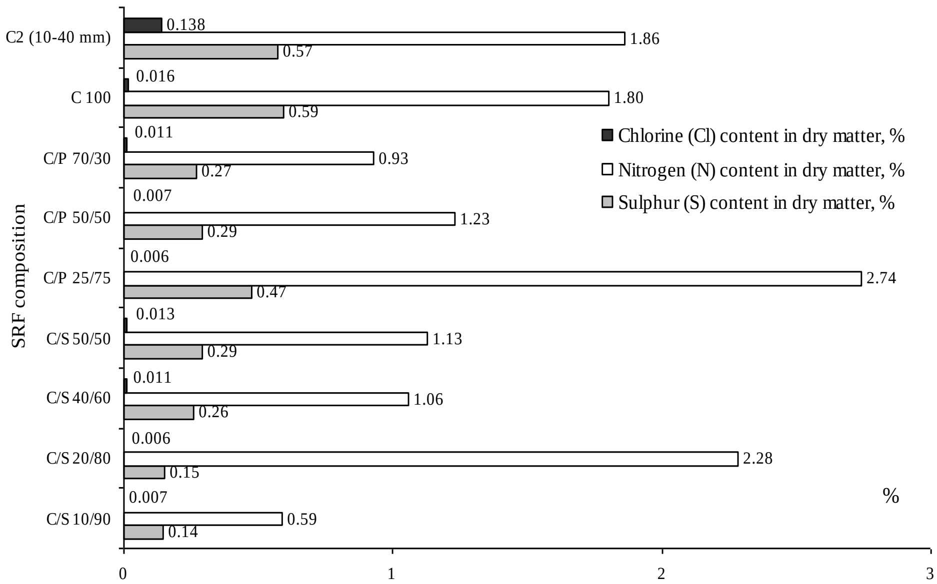


Fig. 6. Chlorine, nitrogen and sulfur content in dry matter, %

Generally, an increase in the compost content in the compound results in an increase in the ash content in dry matter and a decrease in the carbon content (see Fig. 5). SRF of C 100 results in more than 50 % of the ash content. In the case of C2 (10-40 mm) the ash content decreases to 30-31%. It allows concluding that the compost has to be screened for the purpose of separating fraction <10 mm. Only compost fraction 10-40 mm can be used for SRF production. In the further analysis within the Soil-Concept Company it has been evaluated that 10-20 mm fraction compost is the optimal for SRF production [Soil-Concept, KTU APINI 2010, Kliopova at al. 2010].

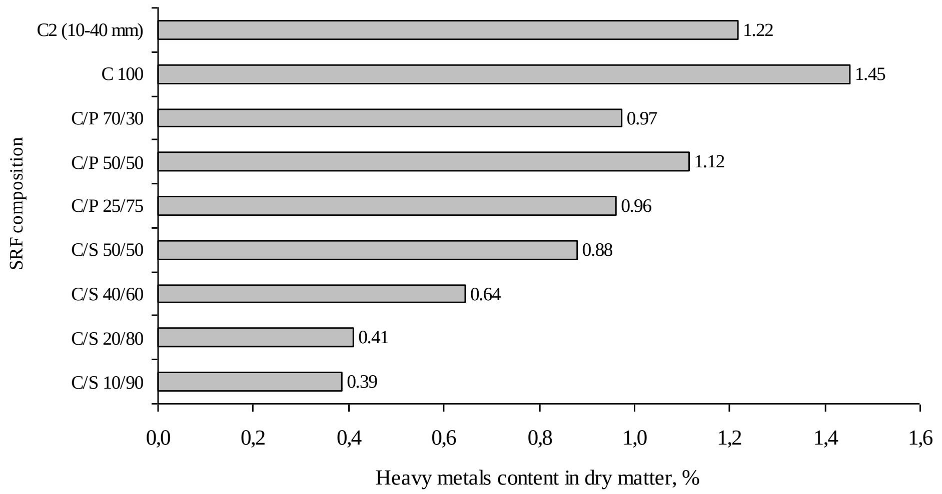


Fig. 7. Content of heavy metals (Cd, Cu, Pb, Ni, Mn, Fe, Cr, Zn, As, Hg) in dry matter, %.

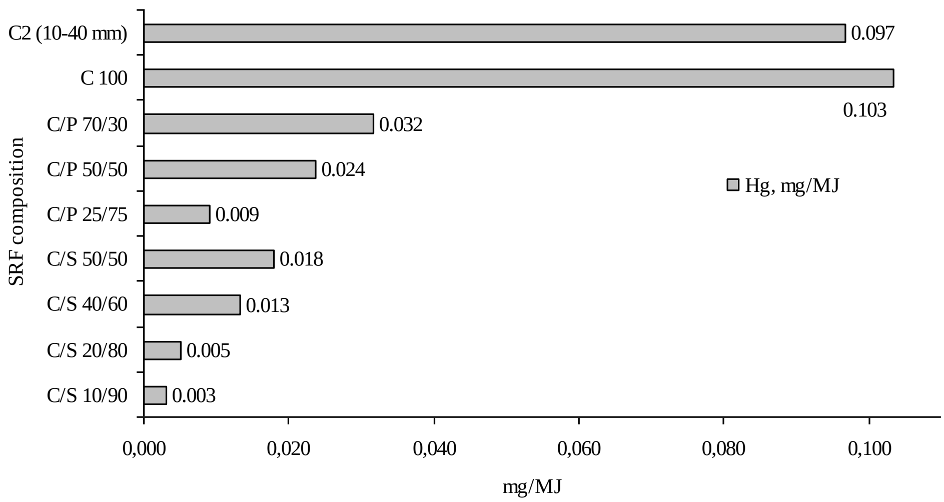


Fig. 8. Hydrargyrum (Hg) content, mg/MJ

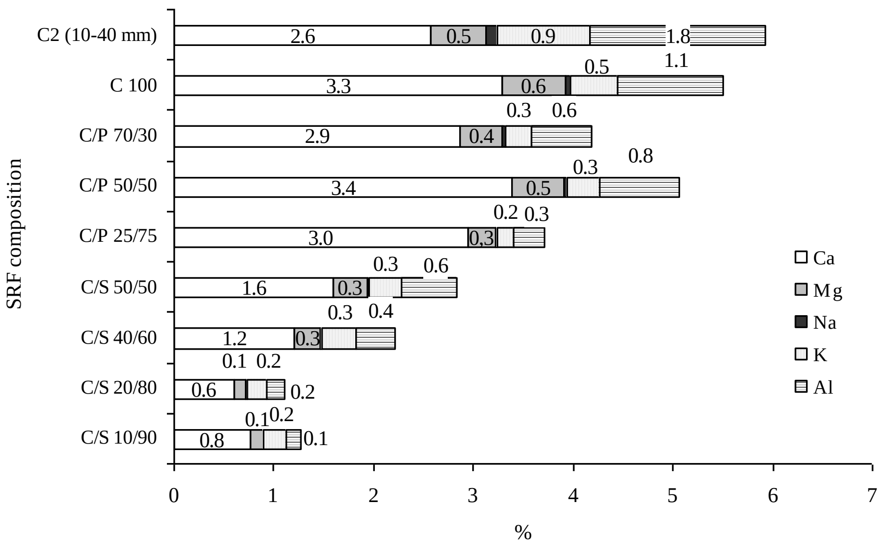


Fig. 9. Calcium (Ca), magnesium (Mg), natrium (Na), kalium (K), and aluminium (Al) content in dry matter (%)

The contents of Cl, S, and N in different compositions of SRF are presented in Figure 6. Generally, the S content increases exponentially with an increase in the compost content. Obviously, if the content of the compost increases, the Cl content also increases.

Sawdust fuel is characterized by a significantly lower N and S content compared to peat fuel and compost [Kliopova at al. 2010]. Therefore, adding sawdust into the compost would reduce the content of Cl, N and S in SRF.

In case the compost content increases, the content of heavy metals also increases (see Fig. 7). Fe (0.363-1.314%), Mn (0.0118-0.0647%) and Zn (0.0066-0.065%) are the most significant heavy metals in produced SRF. Thus, to reduce the heavy metals content in the fuel, sawdust or peat could be added.

It can be noted that an increase in the compost content in the compound results in an increase in the Ca, Mg, Na, K, and Al content: Ca content increases from 0.76% to 3.4%, Mg – from 0.13% to 0.63 %, Na – from 0.013 % to 0.052 %, K – from 0.22 % to 0.9 % and Al – from 0.14 % to 1.8 % (see Fig. 9). Obviously, the maximum content of those elements is in C 100 and C2 (10-40 mm).

The system of SRF classification presented in the CEN/TC 343 standard is based on three main fuel characteristics [European Committee for Standardization CEN/TR 15508:2006, EN 15359:2011]:

- net calorific value (as received - ar),
- chlorine (Cl) content (in dry matter - d),
- mercury (Hg) amount (as received - ar).

Considering the information presented above, part of SRF produced during the experiment is attributed to a certain class of SRF. Results are presented in Table 3. SRF is attributed to class 4 or 5 by the net calorific value, to class 1 by the chlorine (Cl) content in dry matter and to classes 1-4 by the mercury content (see Table 3).

Table 3. Comparison of produced SRF with the classification system of solid recovered fuels (CEN/TC 343)

SRF	SRF form	Conformity to a certain class of recovered fuel in accordance with below presented fuel characteristics					
		Net calorific value (ar), MJ/kg		Chlorine (Cl) content (d), %		Mercury (Hg) content, mg/MJ (median)	
		value	class	value	class	value	class
C/S 10/90	pellets	13.19	4 (>10)	0.007	1 (<0.2)	0.003	1 (<0.02)
C/S 20/80	pellets	12.39	4 (>10)	0.006	1 (<0.2)	0.005	1 (<0.02)
C/S 40/60	pellets	11.31	4 (>10)	0.011	1 (<0.2)	0.013	1 (<0.02)
C/S 50/50	pellets	10.67	4 (>10)	0.013	1 (<0.2)	0.018	1 (<0.02)
C/P 25/75	briquettes	12.72	4 (>10)	0.006	1 (<0.2)	0.009	1 (<0.02)
C/P 50/50	pellets	4.88	5 (>3)	0.007	1 (<0.2)	0.024	2 (<0.03)
C/P 70/30	pellets	5.57	5 (>3)	0.011	1 (<0.2)	0.032	3 (<0.08)
C 100	pellets	3.80	5 (>3)	0.016	1 (<0.2)	0.103	4 (<0.15)
C2 (40-40 mm)	-	*12.01*	*4 (>10)*	*0.138*	*1 (<0.2)*	*0.097*	*4 (<0.15)*

6. Results of testing combustibility of produced SRF

Produced SRF was burned in the small-scale wood combustion plant, which is used for heating industrial premises (e.g. production departments, and storehouses). Main purposes of the recovered fuel combustion were:

1) to evaluate combustion characteristics of produced SRF in small fuel combustion plants;
2) to evaluate concentration of main air emissions (CO, NOx, SO_2, PM) (mg/Nm^3).

All the fuel was burned approx. for 2 h – it is time for optimal measurement of the air emissions. Measurement was made by Ekopaslauga Ltd.

Combustion of SRF fuel from the composition of compost and sawdust proceeded without any technical difficulties. When the compost content increased up to 89 %, the fuel did not burn, it fumed.

SRF from compost and peat burned considerably worse. The combustion process proceeded well only when the recovered fuel from the composition of up to 25 % of the compost was burned (C/P 25/75). In the case of greater content of the compost in the compound, the recovered fuel more fumed than burned.

The volume of PM air emissions was evaluated using the method of weighting, other emissions were electrochemically evaluated with gas analyzer “Multilyser”. Burning each type of the fuel, 3 measurements of PM and 6 measurements of other air emissions were made. Further, the average values of measured indicators were evaluated. Obtained results were normalized - recalculated for 6 % of O_2 concentration (for SRF).

Some results of measurement during successful burning processes of compost and sawdust and their comparison with the norms for co-incineration of bio-mass waste are presented in Table 4. Norms for air emissions (PM, NOx, SO_2)

during waste incineration were taken from paragraph II of article 7 of the Directive 2000/76/EC of the European Parliament and the Council [Directive 2000/76/EC]. This norm is used for bio-mass waste combustion in large combustion plants (LCP: *50≥MW<100*).

In this experiment combustion plant <1MW was used. Therefore, concentrations of some air emissions exceeded permissible norms (see Table 4).

Analyzing the concentrations of the pollutants emitted during the combustion of produced SRF, the following conclusions can be drawn:

- The produced SRF has low emissions of SO_2 (< 100 mg/Nm^3) – lower than the permissible norm for bio-mass waste combustion LCP.
- Large amounts of CO, NOx are emitted to the air during the SRF burning in the small-scale fuel combustion plants, where combustion technologies on firegrates are used, and the control is non-automatic (in case of experiment – CO - up to 5 thousand mg/Nm^3, NOx – up to 670 mg/Nm^3).
- The high CO content indicates that the combustion products may include unburned carbon particles. In the case of an experiment, CO is emitted due to partial (uncompleted) combustion because of, for example, low burning temperature, short continuance in the burning zone. It is necessary to minimize CO volume in the exhaust gas for the purpose of minimizing the risk of corrosion or heat energy losses. Therefore, *fluidized bed combustion (FBC)* or *other technologies*, which are characterized by low CO-emissions due to a high degree of combustion, should be applied [BAT for LCP].
- Mostly, loss of the heat energy during the combustion process is related to the physical heat of combustion products and depends on the combustion temperature and the excess air coefficient (factor) λ ($CO_{2,max}/CO_{2,measureds}$) [Vares et al. 2007].
- On the basis of the combustion products analysis, the optimal value of excess air coefficient λ depends on both combustion technology and the type of fuel. In order to burn the fuel completely, its value must be $\lambda >$ 1 [Staniškis et al. 2010]. When wood fuel, peat, biomass are burned, it is difficult to distribute the combustion air equally over the whole combustion zone, therefore, to ensure the complete combustion, the value of the excess air coefficient must be higher than 1.4 [Vares at al. 2007, Kliopova and Laurinkevičiūtė 2009].
- Since the ash content in SRF is very high, the concentration of PM emissions to the air is very high too. Therefore, a solid particles treatment plant (e.g. cyclone) should be installed. In the case of SRF burning in large combustion plants (LCP), electrostatic precipitators (ESP) are to be installed [BAT for LCP].

Table 4. Comparison of the evaluated concentrations of air emissions during technically successful SRF burning with the norms for co-incineration of bio-mass waste

SRF composition	Average concentrations, recalculated to standard conditions (6% of O_2), mg/Nm^3 ([1,2] *norms for co-incineration of bio-mass waste; 50≥MW<100*)		
	PM (after treatment)	NOx (A)	SO_2 (A)
C/S 10/90 (pellets)	38 *(50)*	495 *(350)*	0.00 *(200)*
C/S 40/60 (pellets)	4 *(50)*	482 *(350)*	0.00 *(200)*
C/S 50/50 (pellets)	16 (50)	670 (350)	0.00 *(200)*
C/S 60/40 (briquettes)	64 (50)	586 (350)	71 *(200)*

Comment:

[1] - only for bio-mass: products consisting of any whole or part of a vegetable matter from agriculture or forestry which can be used for the purpose of recovering its energy;

[2] – norms for other air emissions which were not measured during experiment: (Cd + Tl) ≤0.05 mg/Nm^3; Hg ≤0.05 mg/Nm^3; (Sb + As + Pb + Cr + Co + Cu + Mn + Ni + V) ≤ 0.5 mg/Nm^3; dioxins and furans ≤ 0.1 Ng/N m^3 [Directive (2000/76/EC), Annex II].

6. Conclusions and recommendations

Producing SRF from various compositions of the compost (*made of pre-composted input materials: sewage sludge, green waste, and other biodegradable waste*), sawdust and peat, efforts were made to estimate the possibilities of fuel formation (pressing), and combustibility, to evaluate its impact on the environment during the production and burning processes.

Energy consumption per unit of production is a very important environmental indicator. Evaluating energy consumption per unit of recovered fuel production (kWh/kg), it can be concluded that pelleting process is considerably more energy-intensive than briquetting. For example, to produce 1 t of pellets (C/S 50/50), 384 kWh of energy is used, and to produce 1 t of briquettes of the same composition 120 kWh of energy is consumed. Unfortunately, energy consumption per unit of production, measured during pelleting tests, differs nearly twice, compared to the energy consumption during the sawdust pellets production in Europe, for example, in Austrian sawdust pellets production company - 113.9 kWh/$t_{pellets}$ [Thek and Obernberger

2009], in Lithuanian innovative pellets production companies - from 130 to 190.9 kWh/$t_{pellets}$. In the case of pelleting tests, energy consumption during production of pellets of sawdust and compost was from 220 to 384 kWh/$t_{pellets}$ (*when the compost content increases, energy consumption also increases, since the production process takes more time*). Energy consumption during production of pellets of compost and peat was from 263 to 143 kWh/$t_{pellets}$ (*when the compost content increases, energy consumption decreases*). High energy consumption was due to *old* technology equipment: transporters, stirrer, press, which were used during Project pelleting tests. Furthermore, a small amount of raw materials was pressed, therefore it was complicated to adjust the equipment properly and to optimize the process timewise. This question was particularly analyzed during the following research stages – pelleting press monitoring in the "Soil Concept" Company carried out during 2010 [Soil-Concept, KTU APINI 2010].

Analyzing the impact on the environment during SRF production, it has been assumed that there is a need to produce the amount of the fuel, whose total calorific value is equal to 100 MWh. Such a decision has been made, since the net calorific values of produced recovered fuel differ greatly. This analysis has revealed that the lowest impact on the environment is made during the briquetting process of compost and sawdust, compost and peat, and pelleting compost and sawdust (if the compost content in the compound does not exceed 20 %).

Producing fuel of compost and sawdust, the net calorific value decreases, compared to those of sawdust pellets. For example, the calorific value of sawdust pellets and briquettes must reach minimum 16.9 MJ/kg, according to the solid fuel nomenclature; net calorific value of sawdust briquettes produced in Medinukai Ltd. with 8 % of the moisture content is 18.99 MJ/kg.

In the case of experiment, the best result in terms of the net calorific value was achieved producing the pellets of 10% of compost and 90 % of sawdust, namely, – 13.19 MJ/kg (fuel moisture content– up to 17.31 %), the net calorific value in dry matter of this recovered fuel was 16.47 MJ/kg. The net calorific value of briquettes of this composition would be approx. 16 MJ/kg, since moisture of briquettes is considerably lower.

Likewise, briquettes of up to 25 % of compost and 75% of peat (12.72 MJ/kg of the net calorific value, when the moisture content is 16 %) should have good combustibility characteristics. When the compost content in the recovered fuel compound increases, its calorific value exponentially decreases.

Evaluating results of the laboratory analysis, the produced recovered fuel was compared with the standard requirements for SRF according to CEN/TC 343. The comparison shows that produced SRF corresponds to the standard requirements for the recovered fuel (see Table 3). Nevertheless, it has been decided that compost fraction 10-20-40 can be used for SRF production for the purpose of minimizing the ash content and decreasing the net calorific value. Further, the research has explained that the net calorific volume of such compost increases significantly, for example, the net calorific value of compost with approx. 12% of moisture content is 12.007 MJ/kg [Soil-Concept, KTU APINI 2010]. It corresponds to the net calorific value of non-pressed sawdust or peat with approx. 30 % of the moisture content. In this case, compost can be used for SRF production without being improved with additional materials (sawdust and/or peat).

During SRF combustion and measurement of main air emissions, it is identified that the impact on the air will be significant, if this fuel is burned in small-scale fuel combustion plants: due to the low temperature of combustion and non-automatic control, the combustion process does not succeed completely, therefore, CO concentration in the emitted fume increases, NOx emission level (mg/Nm^3) exceeds the emission limit values (ELV) according to the Directive 2000/76/EC. The theoretical combustion temperature depends on the fuel calorific value and moisture. To optimize the heat energy production process and to reduce the costs of the produced heat energy in small fuel combustion plants, it is advisable to use only higher-quality homogeneous fuel, such as sawdust pellets or briquettes. For burning wood waste and recovered fuel, more complex technological solutions are required and, in terms of economic return, usually *large fuel combustion plants* are recommended.

As in the case of biofuel combustion, in the recovered fuel combustion plant the excess air coefficient (factor) should be maintained at its minimum value of 1.4. Also, due to high dust air emission, solid particles treatment plants are to be installed.

In all EU states, two main topics are relevant in environmental activity, namely, alternative energy sources and utilization of biodegradable waste. As seen from the ENERCOM project, these questions are closely related and can be solved simultaneously: the alternative fuel can be produced from biodegradable waste, for example, pre-composted materials (sewage sludge and biomass residues). Sawdust and/or peat can be added as a raw material for the minimization of environmental impact during SRF production and burning. In the case of the project, waste will be recovered into raw materials for energy production (waste-to-energy).

Summarizing research results, it can be stated that

- it is advisable to produce SRF exactly from pre-composted materials (not only from sewage sludge) because of their better characteristics, such as high net calorific volume, lower moisture content (due to evaporation during aerobic process, i.e. biological drying);
- chemical and physical characteristics of separate compost fractions are to be evaluated for the purpose of discovering more suitable

ones for fuel production for each compost parcel;
- produced SRF should be burned in large fuel combustion plants possessing automatic process control and dust treatment equipment;
- addition of sawdust and/or peat into wood compost improves some SRF characteristics: increases the net calorific volume, reduces the content of ash, Cl, N, S, and heavy metals.

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Kietojo atgautojo kuro gamyba iš buitinių nuotekų dumblo komposto

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(gauta 2012 m. spalio mėn.; atiduota spaudai 2012 m. gruodžio mėn.)

Pastaraisiais metais nuotekų dumblo kiekiai Europos Sąjungoje (ES) vis didėjo. Šio reiškinio priežastis – daugėja gyventojų, įgyvendinami ES direktyvos 91/271/EEC reikalavimai plėsti vandentiekio ir nuotekų surinkimo tinklą ES valstybėse narėse. Lietuva kaip ES narė, vykdydama šios direktyvos reikalavimus, taip pat praplėtė vidaus vandentiekio ir nuotekų surinkimo tinklus. Dėl to padidėjo nuotekų dumblo kiekiai kaip nuotekų valymo šalutinis produktas. Remiantis ES Sąvartynų direktyva 99/31/EC, nuotekų dumblą draudžiama deponuoti sąvartynuose. Todėl ES šalyse ieškoma būdų, kaip efektyviai spręsti nuotekų utilizavimo problemą. Beveik visų ES šalių buitinių nuotekų valymo įrenginiuose yra naudojamos nuotekų dumblo anaerobinio apdorojimo technologijos. Išgautos biodujos naudojamos energijai gaminti. Didžioji dalis energijos sunaudojama pačiame anaerobiniame procese ir tolesnio dumblo apdorojimo procesuose. Taip pat reikia sprendimo, kaip toliau naudoti anaerobiniame procese likusį degazuotą dumblą. Šiuo metu Lietuvoje plačiai analizuojamos galimybės, kaip naudoti degazuotą dumblą atgautajam kurui gaminti. Mokslininkų teigimu, šis dumblas nepasižymi didelėmis žemutinės šiluminės vertės charakteristikomis [Wetle and Wilk, 2010, Houdkova et al., 2008]. Be to, dumblui džiovinti reikia sunaudoti nemažai energijos. Kitose ES šalyse nuotekų dumblas kaip biologiškai skaidi atlieka apdorojamas aerobiškai, t. y. kompostuojamas, maišant jį su kitomis anglies (C) turtingomis medžiagomis. Tam taikomos įvairios technologijos, mažinančios kompostavimo proceso poveikį aplinkai. Kompostuoti galima ir pirminį dumblą, ir anaerobiškai apdorotą. Atliekant komposto cheminių ir fizikinių parametrų tyrimus, buvo pastebėta, kad ši medžiaga arba jos tam tikros frakcijos turi savybių, tinkamų kietajam atgautajam kurui (KAK) gaminti.

2009–2010 m. KTU APINI darbuotojai, vykdydami 7 BP programos projekto „Energijos, kuro ir trąšų gamyba iš biomasės liekanų ir nuotekų dumblo“ (ENERCOM) (Nr. TREN/FP7/EN/218916) etapą „Granulių ir briketų gamybos įvykdomumo analizė“, analizavo komposto naudojimo KAK gamybai galimybes. Vienas iš projekto partnerių – Liuksemburge sėkmingai veikianti komposto gamybos įmonė „Soil Concept“. Šioje įmonėje kompostas iš nuotekų valymo įrenginių degazuoto dumblo ir biomasės liekanų gaminamas atvyto aerobinio apdorojimu būdu su priverstiniu oro padavimu.

Atliekant tyrimą, buvo vertinamos galimybės gaminti briketus ir (arba) granules iš įvairiomis proporcijomis sumaišytų medžiagų: „Soil Concept“ pirminio komposto (po žaliavų sumaišymo ir aerobinio apdorojimo per ~3 savaites, naudojant biodžiovinimo principus), pjuvenų ir durpių. Atlikus eksperimentą, sėkmingai pagaminta 14 KAK rūšių briketų ir granulių. KAK gamybos eksperimentai buvo atliekami UAB „Medinukai“ briketų gamybos įmonėje ir granulių gamybos įmonėje techniškai padedant UAB „Logitrita“. KAK gamybos metu įvertintos kuro formavimosi galimybės ir surinkta informacija, kaip tirti gamybos proceso poveikį aplinkai. Atlikus tyrimą, nustatyti pagaminto KAK pagrindiniai cheminiai ir fizikiniai parametrai: drėgnumas, kaloringumas natūralioje medžiagoje, sausoje medžiagoje, pelenai sausoje medžiagoje, sieros, azoto, anglies, chloro, sunkiųjų ir kitų metalų kiekis sausoje medžiagoje. KAK parametrai įvertinti Agrocheminių tyrimų centro analitinio skyriaus laboratorijoje. Naudojant laboratorinės analizės rezultatus, gauti parametrai buvo palyginti su kietojo atgautojo kuro klasifikacijos sistemoje (pagal CEN/TC 343) pateiktais parametrais. Visas sėkmingai pagamintas kuras atitinka atgautojo kuro charakteristikas. Naudojant surinktus duomenis, buvo įvertintas poveikis aplinkai KAK gamybos metu. Eksperimento metu deginant pagamintą KAK nedideliame kurą deginančiame įrenginyje, išmatuotos degimo produktų emisijos į aplinkos orą. Teršalų koncentracijų reikšmės po normalizavimo palygintos su normatyviniais, deginat kietąjį kurą ir atliekas.

Straipsnyje pateikti visų atliktų tyrimų rezultatai, aprašyti KAK gamybos ir naudojimo galimi teigiami ir neigiami aspektai, pateiktos apibendrinančios išvados ir rekomendacijos.