EFFICIENT ENERGY RECOVERY FROM TEXTILE WASTE AND BIOMASS MIXTURE

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Abstract. Efficient energy recovery from the fuel pellets consisting of waste textile materials and biomass depends on many factors. One of the main tasks is to create a competitive form for the newly offered fuel (pellets from a mixture of biomass and textile), as well using a new generation of small-scale energy production facilities. Roughly estimated the quantities of textiles separately collected will increase from 65 000 to 90 000 tons per year across the EU-27 from 2025. Reuse and recycling outlets will need to be created, as the current sorting and recycling capacities are not sufficient to process the anticipated volumes. However, it is also expected that at least half of these additional volumes will comprise non-reusable textile waste with specific flame retardant (FR) treatment. It is known that flame retardant is hazard by its adverse environmental impacts of FRs in their production and disposal phases. The objective of the paper is to review opportunities of elaboration a new type of fuel pellets and using them in small-scale pellet boilers, and combined heat and power CHP. The new pellets from biomass (prepared by plasticization method) and chopped textile waste sized up to 2-3 mm (by method of separative milling) were elaborated and tested in controlled combustion processes. Experiments were carried out by adding different proportions of textile waste to biomass pellets and the results obtained are summarized in the article.

Keywords: pellets, waste management, efficiency, energy recovery, emissions.

Introduction

Latvia is under its way to achieve the European Union (EU) climate neutrality goals - by 2050, 80% of the total energy consumption is produced from Renewable Energy Sources (RES) (compared to the EU average goal of 40% in 2030 [1]. A significant part of the energy produced by RES is wood biomass (in 2018 62.6 PJ or 80.4% of the total RES consumption) [2]. Energy production from biomass is sustainable although less than from fossil energy sources [3], causes greenhouse gas (GHG) emissions [4; 5]. The main consumers of wood biomass are households (mostly apartment buildings) who use the district heating (DH) net and households that are not connected to DH (mostly private houses)[6].

In the field of textile material recycling, as one part of the renewable energy source, it can be seen that most of the waste is burned, but only less than 1% is used for recycling [7]. Handing over textile clothes and textile materials for repeated use or sending to developing countries does not lead to waste processing, but to its transfer outside the European Union [8]. There is no assurance that in developing countries, after the end of the life cycle of clothes, they would be recycled.

It is indicated that a significant amount of textile materials is stored in landfills for future recycling [9], the study shows potential of having technologies efficient energy recovery from waste materials [10].

The guidelines of the European Green Course promote the use of RES in the production of heat and electricity, as a result of which an increase in the use of biomass can be observed. An increase in the use of granulated biomass in the production [11] of heat and electricity is observed. Pellet heating equipment is one of the most efficient currently available technologies for obtaining energy from biomass [11; 12]. The directives and policy documents of the European Union on the use of biomass for heating promote efficient and sustainable use of this resource [13], as a result of which energy sector companies that use biomass as fuel for heat and electricity production are expected to face greater competition for the extraction of raw materials for fuel production [14].

In this perspective, the boundaries of using composite materials for recycling can be expanded, including polymer structures with various inclusions of natural·s⁻¹ynthetic particles [15-18], including nanomaterials [19-21], as well as widely used polymer matrix composite materials, such like concrete reinforced with fibers [22; 23].

Textile waste incineration currently takes place in specialized waste incineration plants, but no waste incineration is observed in heating facilities [24]. Taking into account that a significant part of textile waste is deposited for later processing, it can be assumed that in the future technologies and

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opportunities for efficient processing of textile waste will be available. Therefore, the preparation of new type pellets responding to the EU ISO 17225-2:2021standard is very relevant and timely.

By developing a new type of fuel, which would consist of biomass/wood processing residues and a mixture of waste textile materials, it would be possible to use the waste to efficiently process it in already existing heating facilities, without using specialized waste incineration plants [25]. The research explores in an experimental way the possibilities of creating fuel that could be used in already existing pellet heating facilities.

The objective of the research is to develop novel high-calorie and low-emission heating pellets from the waste of synthetic/natural textile materials and biomass (which cannot be recycled into new textile material) for using in household pellet heating boilers.

To reach the objective, a new manufacturing approach to the waste synthetic/natural textile with biomass will be developed, the prototype of the pellets will be manufactured and experimentally tested (mechanical and thermal characterizations according to EN 14961-2; ISO 17225-2:2021).

Materials and methods

To prepare textile fibers (organic/synthetic textile material) of short length an experimental laboratory module was used: high-speed grinding-separation system DS-37/21 (The Research and Testing Laboratory of Materials Recycling, Tallinn University of Technology, (EE), TalTech), that provides the high-speed separative milling of small volumes of various types of textile waste in order to obtain fibres of the required length.

The method of dry high-speed grinding-separation of worn-out textile materials was applied to prepare the short length textile fibers or powdered fibers (3 ± 1 mm).

Concept/Description of the fiber preparation: the feeding/dosing system consists of a screw conveyor that transports the pieces of the material through a unit of preliminary mechanical processing. The drive power was 1.5 kW, preliminary processing system power was 2 kW. The material (max length of material pieces was apr. 0.5-1 m) was milled in the grinding system, and the obtained fibers flied to the separation unit with the air flow.

The grinding drive power was 3 kW. The maximum engine rotation speed was 3000 rpm. The range of linear processing speed was 120 m·s^{-1}.

Then, the milled fibers were divided in the separation system. The fibers of the required size (3 ± 1 mm) were separated (under the influence of inertial force) and fed to the finished product collector. Large/insufficiently chopped·m^{-1}illed fibers were fed for re-processing.

The performance of the system (depends on the degree of preliminary processing, material properties) was organic·s^{-1}ynthetic textile material – 2 kg·h^{-1}, cotton material – 1.5 kg·h^{-1}. Other characteristics (in first approximation), like as the type of weaving, relative humidity, structure and thickness of the thread, linear speed and configuration of the milling cutter and the required particle size of the product are not taken in consideration in this manuscript and were regarded as a constant.

Cotton material was used: woven fabric; purchased in the store of illiquid raw material shop "Abakhan", Tallinn, Estonia; plain weave, surface density 244 ± 5 g·m^{-2}. The specimens of the powdered fibers (24 h technological deposit, room temperature 22 ± 1 ℃; moisture content 60%, according to ISO 139:1973) were used to prepare the pellets.

PES (Polyester) material was used: knitted fabric; purchased in the store of illiquid raw materials shop "Abakhan", Tallinn, Estonia; combined knitted weave, surface density 185 ± 5 g·m^{-2}. The specimens of the powdered fibers (24 h technological deposit after the grinding process, room temperature 22 ± 1 ℃; moisture content 60%, according to ISO 139:1973) were used to prepare the pellets.

Pinewood chips were received from a woodworking factory. The equipment to prepare the pellets is the pellet machine ZLMP400. Four combinations of the pellets and one type from pure pine wood chips were prepared (Table 1).

To determine the length and diameter of the received pellets the Electronic digital caliper was used (Resolution: 0.1 mm/0.01"; Accuracy: $\pm$ 0.1 mm/0.01"; Battery: SR44/LR44 1.5 V; GE).

Table 1

Composition of the pellets

No	Types of combination	Composition, %
1	Pinewood chips and powdered fibers (Cotton material)	80% & 20%
2	Pinewood chips and powdered fibers (Cotton material)	87.5% & 12.5%
3	Pinewood chips, powdered fibers (Cotton, and PES material)	90% & 5%; 5%
4	Pinewood chips and powdered fibers (PES material)	90% & 10%
5	Pinewood chips	100%

Moisture content of all five specimens was detected according to the standard LVS EN ISO 18134-1. A clean, dry container was weighed with an accuracy of up to 0.1 g. The mass of the specimens should be at least 300 g (it is the weight of the container with the specimens). To determine the floating effect, before drying, the weight of an identical empty and clean reference container with an accuracy of up to 0.1 g was used.

The container with the specimen and the reference container were placed in a drying oven with a temperature of 105 ± 2 ºC, the drying process lasts until the mass of the specimen becomes constant, but no longer than 24 hours (to prevent the release of volatile compounds). The container with the specimens and the empty reference container were weighed on the scales within 10-15 seconds after removing them from the drying oven; a heat-resistant plate must be placed on the scales.

The specimens should be placed in the drying oven so that air can freely flow between them, and moisture can evaporate.

Ash content for dry mass was detected according to the standard LVS EN ISO 18122. An empty and cleaned crucibles are placed in a muffle furnace and heated for at least 60 minutes at a temperature of 550 ± 10 ºC.

The crucibles are placed in a desiccator fitted with a thermocouple and allowed to cool for 25 minutes to reach a constant crucible mass, after which the temperature is recorded, which is recorded in the work report. The cooling time of the container is determined to reduce the mass changes caused by the temperature and to reduce the measurement error. When the crucibles have cooled, their mass is determined with an accuracy of 0.1 mg. The sample materials were mixed and put about 1 g in the specimen crucible in an even layer, no more than $0.1 \, g \cdot cm^{-2}$.

Crucibles with specimens were placed in a muffle furnace and heated in the following sequence:

- evenly heated for 30-50 minutes to $+ 250$ ºC (temperature rise 4.5-7.5 $ºC \cdot min^{-1}$),
- maintained at $+ 250$ ºC for 60 minutes to evaporate volatile substances before igniting,
- then the temperature was raised evenly to $+ 550 \pm 10$ ºC for 30 minutes and maintained at $+ 550 \pm 10$ ºC for at least 120 minutes.

As soon as the set temperature is reached in the desiccator, previously recorded in the work protocol, the mass of crucibles and ash begins to be determined.

GHV (Gross heating value), $MJ \cdot kg^{-1}$ and NWV (Net heating value), $MJ \cdot kg^{-1}$ calorific values were detected according to the standard LVS EN ISO 18125.

The determination of the heat of combustion consists of two separate experiments. The calorimeter is first calibrated using a benzoic acid calibrant, which has the known highest heat of combustion. Calibration is necessary to ensure accurate measurements. After the calibration of the calorimeter, a test to determine the heat of combustion of the fuel is performed. At least two replicates are required for a representative result. The energetic value of the analysed specimen cannot differ by more than $120 \, J \cdot g^{-1}$ for both replicates. To determine the amount of heat (J) produced by the combustion of an acetobutyrate capsule or crucible, they must be weighed on an analytical balance and their mass (g) multiplied by the heat of combustion ($J \cdot g^{-1}$) of the acetobutyrate capsule or crucible. The calorific value of combustion of auxiliaries is excluded from the calorific value of fuel.

The mass of the pellet of the fuel specimen is indicated in the calorimeter, as well as, if necessary, the heat of combustion of the used ignition aids (cotton thread, acetobutyrate capsule, ignition crucible) is entered.

After the test work, the heat of combustion H0 (J·g^{-1}) of the specimen burned in the calorimetric bomb is recorded in the protocol.

Results and discussion

The physical parameters (lengths and diameters) of five types of the pellets were measured useing electronic digital calliper; the results are in Table 2.

Table 2

Physical parameters of the pellets

No	Types of pellets	Average length, $n_{al} = \Sigma n_{100}/100$, mm	Length (mm) according to standard ISO 17829	Average diameter, $n_{ad} = \Sigma n_{100}/100$, mm	Diameter (mm) according to standard ISO 17829
1	Pinewood chips and powdered fibers (Cotton material)	15.45	$3.15 < L \leq 40$	6.62	6 ± 1
2	Pinewood chips and powdered fibers (Cotton material)	17.84	$3.15 < L \leq 40$	6.19	6 ± 1
3	Pinewood chips, powdered fibers (Cotton, and PES material)	15.57	$3.15 < L \leq 40$	6.28	6 ± 1
4	Pinewood chips and powdered fibers (PES material)	15.3	$3.15 < L \leq 40$	6.27	6 ± 1
5	Pinewood chips	21.51	$3.15 < L \leq 40$	6.5	6 ± 1
Average values		**17.13 mm**	-	**6.37 mm**	-

The visual comparative assessment of the physical parameters of the pellets with the allowable values of the standard ES17829, the image shows graphically (Fig. 1).
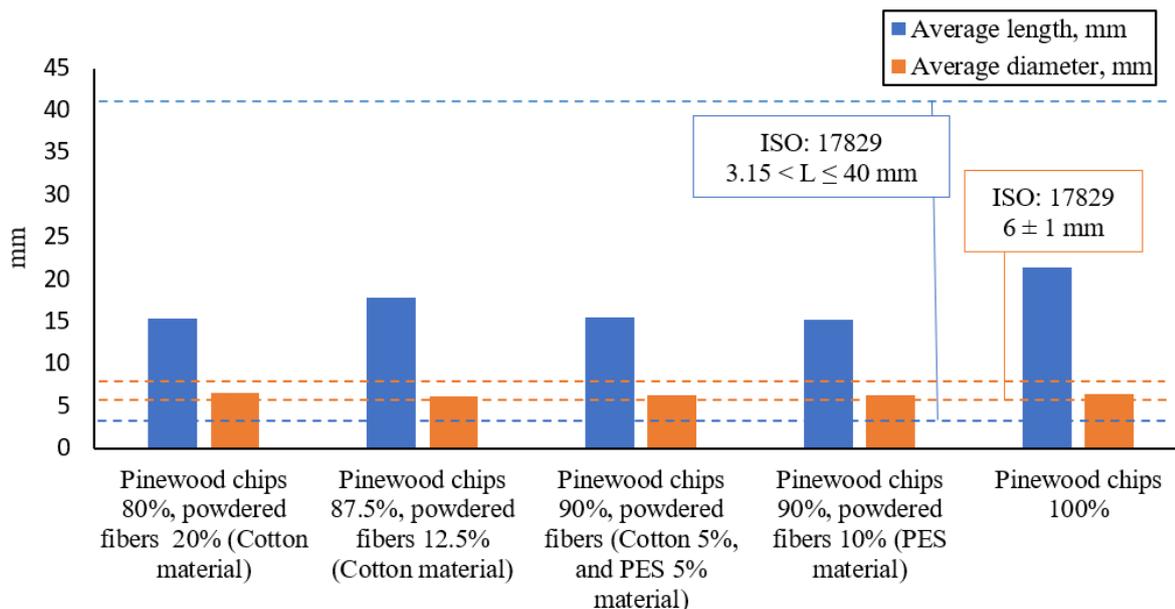

Fig. 1. **Comparison graph of average of lengths and diameters of five pellet types**

In the first phase of the research the physical parameters of the pellets were measured according to the standard ISO 17892. We researched the average length (from 15.3 mm to 21.51 mm) and diameter (from 6.19 mm to 6.62 mm) of the pellets, and the results were compared with the standard ISO 17892, where it is seen that the physical parameters of the pellets are in a proper range allowed in the standard for all five specimens. Studies have shown that the powdered fibres (both types: cotton and PES powder) added in pinewood chips are not influencing the pellet size (as follows from the testing results shown in Table 2).

The standard LVS EN ISO 18125 controls the ash content after pellet combustion. The ash content factor may depend on many factors [26-28], but our research shows the correlation between cotton powder added and ash content [29]. The first two specimens of the pellets (Table 3) contain wood chips and cotton powder in different proportions (1st specimen - 20%, 2nd specimen - 12.5%), and show the ash content higher than in the specimen with 10% synthetic (PES) powder (4th specimen, Table 3). The test results of all five specimens indicate increase of the ash content in the specimens with textile powder (as additive); where the 5th specimen (without textile powder) had the lowest ash content (0.35%), and the 1st specimen (with 20% cotton powder) had the highest (1,58%) ash content. Investigation of the 4th specimen (wood chips with 10% PES powder) shows the lowest ash content 0.43% (among specimens with additives). This result of the ash content can be explained by the fact that in time of combustion PES powder the products were comprised of carbon (C), hydrogen (H_2), oxygen (O_2), and nitrogen (N_2); hydrogen, oxygen, and nitrogen are gases [30; 31].

Table 3

Combustion process laboratory results

No	Types of pellets	Moisture content, %	Ash content, %	Gross heating value (GHV), MJ·kg^{-1} (Tables in the standard LVS EN ISO 18125)	Net heating value (NHV), MJ·kg^{-1}
1	Pinewood chips, powdered fibers (Cotton material)	17.23	1.58	19.7	14.77
2	Pinewood chips, powdered fibers (Cotton material)	14.38	1.05	19.74	15.40
3	Pinewood chips, powdered fibers (Cotton, and PES material)	12.50	0.71	20.12	17.23
4	Pinewood chips, powdered fibers (PES material)	12.59	0.43	20.39	16.34
5	Pinewood chips	12.68	0.35	20.48	16.87

In order to explain how the energy density of the fuel changes, it is necessary to take into account its constituent raw materials. Pellet energetic dencity values have influence by lignin content in the pellets (one of the biomass components), and concentration of lignin in the pellets has influence on the energetic density of the fuel and ash content after pellet combustion [32]. The ash content is affected by non-combustible ingredients in the fuels [32]. This follows from the research, that is, the 1st specimen has higher ash content 1.58% and the lowest fuel energetic value 14.77 MJ·kg^{-1} comparing with the other specimens. The moisture of the raw material in the specimens has influence on the energetic value, for example, moisture of the 1st specimen is 17.23% and its energetic value is 14.77 MJ·kg^{-1}; 2nd specimen: moisture 14.38%, energetic value is higher - 15.40 MJ·kg^{-1} (comparing with the 1st specimen). Obviously, this result was influenced by the content of additional textile cotton powder in the pellets. The first two specimens have higher moisture content, numbers of research [33-35] justify corelation between the biomass moisture content and the energetic value. The high moisture content of the specimen 1st and 2nd may be affected by the hygroscopicity of the cotton fibers. It is known that

cotton fibers have high hygroscopicity (the ability to absorb moisture). During swelling the fibers increase in volume by about 40% [36; 37].

The low heating value (LHV) or net heating value is the energy value of fuel combustion, obtained depending on the actual composition of the pellet material and its moisture content. The high heating value (HHV) or gross energetic value depends on the fuel composition where humidity is not included in calculation[38] and the gross energetic value of each type of material is determined according to the tables with the standard LVS EN ISO 18125. The comparative analysis between HHV and LHV shows very small difference 0.2% between the energetic values of the specimens, that is: 1.3% for the 1st and 2nd specimens, and 1.17-1.25% for the 3rd, 4th, and 1.8% for the 5th specimen, calculated as the difference between the specimens. From this research it follows that textile powder adding practically has no influence on the gross energetic value. The net LHV depends on the water content in specimens [38], represents the correlation between the moisture content and LHV, what is shown in Table 3 and for visualization shown graphically in Fig.2. The most higher 17.23 MJ·kg⁻¹ value of LHV is shown by the 3rd specimen (90% pinewood chips, 5% of cotton powder, 5% of PES powder), as the optimal result of the content of additives for this particular study, despite the middle ash content 0.71% (with comparison among of all five specimens).
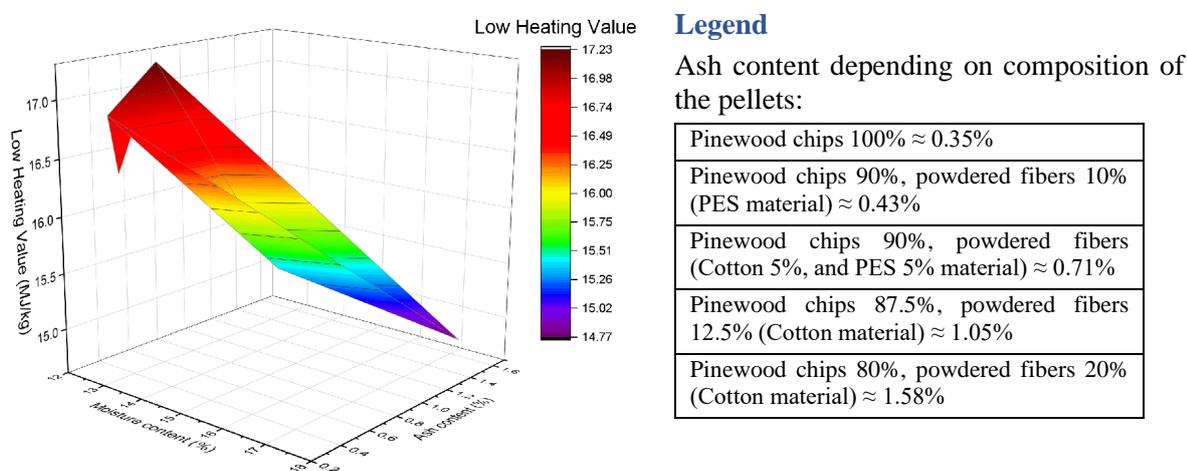

Legend

Ash content depending on composition of the pellets:

Pinewood chips 100% ≈ 0.35%
Pinewood chips 90%, powdered fibers 10% (PES material) ≈ 0.43%
Pinewood chips 90%, powdered fibers (Cotton 5%, and PES 5% material) ≈ 0.71%
Pinewood chips 87.5%, powdered fibers 12.5% (Cotton material) ≈ 1.05%
Pinewood chips 80%, powdered fibers 20% (Cotton material) ≈ 1.58%

Fig. 2. **Comparison graph of LHV, moisture and ash content**

Conclusions

1. The powdered fibers (both types: cotton and PES powder) added in pinewood chips are not influencing the pellet size, where the average length is 17.13 mm, and average diameter is 6.37 mm.
2. The pellets containing pinewood chips and cotton powder (1st specimen - 20%, 2nd specimen - 12.5%) showed the highest moisture content (1st specimen - 17.23%, 2nd specimen - 14.38%) and, as a result, LHV (1st specimen - 14.77 MJ·kg⁻¹, 2nd specimen - 15.40 MJ·kg⁻¹) was less than for the other three specimens.
3. The ash content of the 1st and 2nd specimen is 2.65% higher than for the other three specimens.
4. The highest 17.23 MJ·kg⁻¹ value of LHW is shown by the 3rd specimen (90% pinewood chips, 5% of cotton powder, 5% of PES powder), as the optimal result of the content of additives for this particular study, despite the ash content 0.71%.
5. All five specimens meet the standards to be useful in residential and industrial heat boilers.

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Author contributions

Conceptualization, J.K.; methodology, J.K. and E.V.; validation, S.P.K. and D.G.; formal analysis, D.G. and J.K.; investigation, J.K., E.V. and D.G.; data curation, S.P.K.; writing - original draft preparation, J.K.; writing - review and editing, J.K. and S.P.K.; visualization, S.P.K; project administration, J.K. and E.V.; funding acquisition, J.K. and E.V. All authors have read and agreed to the published version of the manuscript.

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